2013

Food resource availability for Carnaby's cockatoo Calyptorhynchus latirostris on the Swan Coast Plain

Teagan Johnston
Edith Cowan University

Food resource availability for Carnaby's cockatoo *Calyptorhynchus latirostris* on the Swan coastal plain

---

Teagan Johnston

Masters of Science (Biological Science)

School of Natural Sciences, Edith Cowan University

2013

Abstract

To achieve a balance between sustainable development and conservation of threatened species, management depends on understanding the predicted response and interaction of that species with their environment in order to develop appropriate mitigating solutions. The Carnaby's cockatoo *Calyptorhynchus latirostris* is declining across much of its range due to the detrimental effect of habitat degradation and loss. Since the decline of food resource availability in non-breeding areas is believed to be contributing to the reduction in the number of Carnaby's cockatoos knowledge of the birds' foraging ecology and the influence of external factors on food resource availability is essential for effective management. Despite extensive studies and conservation work on the Carnaby's cockatoos, there remain many gaps in our understanding of the birds' foraging behaviour. The aim of this thesis is to fill some of those gaps.

Carnaby's cockatoos are destructive feeders, removing plant parts with strong beaks by holding them while extracting seed and insect larvae. Surveys of the birds feeding preferences were analysed by recording feeding residues of the number of eaten and uneaten infructescences left behind on the ground following foraging bouts. It was noted that Carnaby's cockatoo diets were highly variable in terms of plant structures and species manipulated and consumed. Twenty-four species of food plants were manipulated by Carnaby's cockatoo. Of these, 15 species of plant were consumed for seeds, with 53% of the total being made up of proteaceous species. Six of the 15 species (all *Banksia* species) were also manipulated as inflorescences. Grubbing for insects that were living in or on the woody stem tissue was observed in 63% of the food resource plant species collected. Carnaby's cockatoo displayed a strong preference for food resources of the *Banksia* and *Hakea* genera.

The relationship between Carnaby's cockatoos and *Banksia* species was further examined to understand infructescence availability and variability in seasonal and total annual counts to determine the amount of potential food available to Carnaby's cockatoos. *Banksia attenuata, B. grandis, B. ilicifolia, B. menziesii, B. prionotes and B. sessilis* were targeted in this study. Infructescence availability was determined through examination of Carnaby's cockatoo feeding residues and numbers of mature infructescences that make up the standing crop of infructescences containing seeds. *Banksia* infructescences were available throughout the study for five out of the six species, although seasonal and annual amounts available varied. The numbers of infructescences available were not significantly ($P > 0.05$) influenced by soil type. However, infructescence numbers were significantly ($P < 0.05$) reduced by the

presence of *Phytophthora cinnamomi*. In general the number of infructescences significantly ($P < 0.05$) increased as post-fire age increased.

Plant allometric relationships between morphological characteristics and number of infructescences were investigated to help identify factors which best predict infructescence numbers. For *B. attenuata*, canopy volume, canopy area and girth emerged as the best individual predictive models for explaining the variability of the number of infructescences. Multiple linear regression of all *B. attenuata* plant morphological variables accounted for 29% of the variability in the number of infructescences. Canopy volume, canopy area, girth and foliage height were the best individual predictive models for determining the number of infructescences for *B. menziesii*. The combination of all *B menziesii* plant morphological characteristics explained 44% of the variability in the number of infructescences. All the models tested for *B. sessilis* revealed significant ($P < 0.05$) relationships with correlation coefficients > 53%. Canopy area was the best individual predictive factor for *B. sessilis,* accounting for around 90% of the variation. Multiple linear regression analysis combining all *B. sessilis* plant morphological variables revealed a correlation coefficient of 92%. In comparison to *B. attenuata* and *B. menziesii* (resprouters), *B. sessilis* is an obligate reseeder which is killed by fire. As a consequence of reseeding post-fire, *B. sessilis* commonly occurs in dense thickets and are often more uniform in plant size, age and infructescence availability than resprouters and therefore displays stronger allometric relationships. Determining the influence of external factors on infructescence numbers helps in establishing the amount of food resources available for Carnaby's cockatoos and in turn highlights the importance of various food resource habitats.

Banksia species investigated as part of the food resource availability study were further examined to determine temporal variability of infructescence use by Carnaby's cockatoo. Carnaby's cockatoos showed themselves to be tolerant of changing resource availability which allowed them to effectively utilise food resources across the landscape throughout all seasons. Approximately 50% of resources available were utilised by Carnaby's cockatoo throughout the year, with around 80% of handled infructescences consumed. Carnaby's cockatoos showed flexibility in diet, with temporal variability in food resource use throughout the year. Infructescence resource use was highest between April and September. Level of consumption was a direct result of infructescence availability with no significant differences recorded in infructescence use in the presence of *P. cinnamomi* and different post-fire age stands.

Seed energetics and proportion of seeds and follicles available and consumed were investigated to determine the number of infructescences required to meet daily

metabolic requirements of Carnaby's cockatoo. Over 65% of infructescences handled were consumed for seed for each *Banksia* species. *B. sessilis* recorded the largest number of infructescences and follicles manipulated by Carnaby's cockatoos. The energy content of *Banksia* seeds ranged from 20-23 kJ g^{-1}. Seed weight varied from 0.075g ± SE 0.016 for *B. attenuata* to 0.007g ± SE 0.002 for *B. sessilis*. The number of infructescences required to meet the birds' daily energy intake ranged from 14 for *B. grandis* to 3821 for *B. sessilis,* based on mean number of follicles manipulated for seed and one-hundred percent seed availability. Incorporation of the potential number of seeds per follicle increased the number of infructescences required: *B. attenuata*, *B. ilicifolia, B. menziesii* and *B. sessilis* increased by almost 200%, while *B. prionotes* and *B. grandis* increased by 200% and 300%, respectively.

Information collected on plant morphology, structure and infructescence availability combined with infructescence consumption and seed energy reward by Carnaby's cockatoos allowed the development of food resource algorithms to guide habitat quality assessment. Establishment of quantitative criteria for assessing habitat quality for Carnaby's cockatoo, such as methods for determining food resource availability, allows for effective integration of biodiversity issues into planning and impact assessment processes. The research undertaken for this thesis will add to the understanding and conservation of Carnaby's cockatoo, an iconic South Western Australian species.

Declaration

I certify that this thesis does not, to the best of my knowledge and belief:

(i) incorporate without acknowledgement any material previously submitted for a degree or diploma in any institution of higher education;

(ii) contain any material previously published or written by another person except where due reference is made in the text; or

(iii) contain any defamatory material.

I also grant permission for the Library at Edith Cowan University to make duplicate copies of my thesis as required.

Teagan Johnston

Acknowledgements

It is hard to believe three years have passed since starting this project. I would like to reflect back on the experience and thank the many people who without their support and help this project would have never been fully realised. To my supervisors Professor Will Stock, Dr Robert Davis and Dr Peter Mawson I extend my greatest thanks: Will who was bombarded with questions, to Rob who was always a friendly face to have a chat and Peter whose laissez-faire approach, had the experience to guide an aspiring researcher. Taking on a project such as this was always going to be a challenge but the experience was made more enjoyable and interesting due to the involvement of my supervisors.

I would like to extend my appreciation to all those willing (and some not so) volunteers who battled the heat, storms, snakes and ticks with me, without your support it would not have been possible. Your assistance in the field was greatly appreciated. In alphabetical order these wonderful people are: Mark Angeloni, Rhonda Barbut, Melissa Bastow, Kendal Becu, Heather Beswick, Erin Biggs, Mark Blythman, Peta Bolz, Danielle Bowler, Clare Caldira, Fiona Carpenter, Wendy Chow, Jane Clarkson, Julia Coggins, Abby Crawford, Mike Davis, Jessica Davis, Kirsty Dixon, Alan Elliott, Amanda Fairs, Maura Garry, Christine Groom, Amanda Hook, Jareth Howard, Dan Johnston, Pat Jones, Lesley Judd, Skye Kelliher, Rebecca Kay, Cressida Lehmann, Caron Macneall, Edna McLaughlin, Matt McLaughlin, Tim Moran, Amy Mutton, Anna Nowicki, Raul Ochoa-Hueso, Garry Ogston, Rhys Papas, Grace Patorniti, Kylie Payne, Holly Raudino, John Riley, Evan Roberts, Myrto Roberts, Samara Rogers, Karen Smith, Trevor Smith, Andy Spate, Chloe Sykes, Paul Tholan, Nikki Towell, Belinda Walker, Mikahla Wells, James Widenbar, Alan Wright and Lei Zhang.

To the agencies, organisations, staff, site mangers and property owners that made it possible to access each of the sites, thank you (in no particular order):

Chris Rafferty, Whiteman Park
Veronica Newbury, Bold Park
Steve Easton, Kings Park
Mark Sawle, Headmaster, Aquinas College
Peter Shaw, Dean of Business and Finance, Aquinas College
Kim Patiniotis, Personal Assistant to the Headmaster, Aquinas College
Jan King, Coordinator Mt Henry Peninsula Conservation Group
Alan Elliott, Kingia, Property Owner
Marrion Elliott, Kingia, Property Owner

Midge Richardson, Lowlands, Property Owner
Mark Angeloni, Lowlands, Property Manager
Jessica Bridge, Star Swamp, City of Stirling
Murray Woods, Star Swamp, City of Stirling
Keith Armstrong, Craigie Bushland, City of Joondalup
Heather Beswick, DEC, Yanchep National Park
Julia Coggins, DEC, Yanchep National Park
Alison Pritchard, DEC, Yanchep National Park
Tim Fisher, DEC, Regional Park, Operations Officers
Robert Campbell, DEC, Regional Park, Operations Officers
Tania Irving, DEC, Regional Park, Operations Officers
Alan Wright, DEC National Park Ranger
Craig Olejnik, District Nature Conservation Coordinator Swan Coastal
Bob Cooper, Harry Waring Marsupial Reserve

In particular I would like to thank Alan and Marrion Elliott and Midge Richardson for allowing me to utilise their properties for my research and for the wonderful conversations about Carnaby's cockatoos and their kind hospitality during my visits.

Thank you to those people who provided technical support both verbal and material, your assistance was always greatly appreciated and welcomed. I would like to thank Christine Cooper, Curtin University, and Phil Withers, University of Western Australia, for allowing me to utilise the bomb calorimeter. In particular I would like to thank Christine for providing the training and support whilst at Curtin University. Ron Johnstone, WA Museum, Hugh Finn, Murdoch University, Leonie Valentine, University of Western Australia, Allan Burbidge, DEC, Geoff Barrett, DEC, and David Mitchell, DEC, provided support and technical advice early on in the project, which provided a good grounding. To Tony Kirkby, WA Museum, thank you for taking the time in the field to show me key signs of feeding and considerations when in the field. I am grateful to Ricky van Dongen, GIS DEC, who was the 'go-to-guy' for GIS support, your knowledge and guidance was invaluable to the project. I would like to thank the Threatened Seed Centre staff (DEC) for their assistance in seed processing. In particular, I would like to thank Andrew Crawford DEC, who helped arrange access to the DEC's seed centre for seed processing and for arranging for a storage facility for all my plant material, which without I would have been buried alive by boxes in my office and at home. I would also like to thank Karen Smith (aka Mum) and Manda Page DEC, for editing chapter drafts, your assistance was greatly appreciated.

Lastly, but by no mean least I feel grateful, privileged and honoured to have a very loving and understanding husband, Dan Johnston. Boxes of *Banksia* plant material often littered the house, hiding the dining table and filling the air with a sweet scent of decay. His support kept me going during the long days in the field and when I became housebound due to shoulder surgery and a broken foot (not at the same time). Dan was always ready to help however possible from assisting in the field on weekends, allowing our oven to bake *Banksia* cones instead of biscuits and taking on the role of tick checker. His willingness to share the occasional eight legged bed partner was above and beyond husbandly duties.

This project would not have been possible without financial support from the Fiona Stanley Hospital Environmental Management Conservation Initiatives Offsets Package and assistance from the Department of Environment and Conservation (WA).

Glossary

Cone: A woody multiple fruit incorporating the bracts and bracteoles associated with the flowers.

Fruiting structures: The seed-bearing structures formed from the ovary after flowering. Collective term used to describe cones (e.g. *Pinus*), nuts (e.g. *Eucalyptus*), infructescence (e.g. *Banksia*) and fruit (e.g. *Hakea*).

Inflorescence: A group or cluster of flowers arranged on a common stem that is composed of a main branch or a complicated arrangement of branches. This term includes the developing, flowering and fertilised stages of an inflorescence.

Infructescence: The fruiting stage of the inflorescence. For the purpose of this thesis, infructescence will only refer to mature infructescence of *Banksia* species, in which follicles are fully developed.

Drying infructescence: Infructescence with fully developed closed follicles.

Reproductive structures: Refers to inflorescences, flowers and fruiting structures (fruits, cones, nuts and infructescence) and associated developing stages.

Table of Contents:

Chapter 1: General Introduction

The following thesis is a study of Carnaby's cockatoo *Calyptorhynchus latirostris*, an endemic species of South Western Australia, which has been identified as a species of conservation concern and as such receives legal protection. As a threatened, iconic and relatively large avian species, the Carnaby's cockatoo receives much interest from professional ecologists, urban planners and amateur naturalists alike. However, before embarking upon a description of the birds' biology and ecology, it is appropriate to briefly address the broader issues and reason for this study. This will be followed by Chapter 2, Study System, which outlines the life history and status of the Carnaby's cockatoo, importance of *Banksia* species as a food resource, limitations to food resource availability and introduces the study area and site selection process. Finally, a thesis outline is presented which gives brief descriptions of each data chapter to provide a framework to this study.

1.1 Introduction

Western Australia's patterns of urban and agricultural growth have contributed to a substantial loss of biodiversity (State of the Environment Report Western Australia 2007). The area subject to urban development along the Swan River and adjoining coastline has increased from 378 km² in 1974 to 830 km² in 2008 (Western Australian Planning Commission 2010). Perth's relatively short history has seen it change from a small colonial outpost to a major city. Established as a small European settlement on the Swan coastal plain primarily with agricultural ambitions, the city settlement increased in size as the primary port for prospectors and their ilk on their way to the Goldfields (Stannage 1979). Agricultural land was soon over taken and replaced with industry and urban development. Since 1900 the population of Perth has outpaced resources, from water supply and infrastructure to land for development (Weller 2009).

It is predicted that by 2031 the population of the Perth and Peel regions will be around 2.2 million, an increase of more than half a million residents in a little over two decades (Western Australian Planning Commission 2010). The greater Perth area falls within one of the world's 34 biodiversity hotspots. Increased urban growth is placing greater pressure on this diverse and unique environment (Myers *et al.* 2000). Managing anthropocentric values to achieve an acceptable balance between conservation and socio-economic objectives is complex and a challenge for conservation agencies and land managers. Therefore information on species distribution, life history and resource use across different spatial and temporal scales is required to predict habitat suitability for species subject to environments which are in a state of flux.

The Carnaby's cockatoo, *Calyptorhynchus latirostris,* has experienced a significant decline in population size and extent of its range over the past 60 years, which has generally been attributed to a reduction in the availability of suitable foraging and breeding habitat (Saunders 1990; Johnstone & Storr 1998). Extensive land clearing for agriculture and urban development has resulted in the once abundant species being listed as threatened in Western Australia under State (W*ildlife Conservation Act 1950)* and Commonwealth (*Environment Protection and Biodiversity Conservation Act 1999)* legislation. Carnaby's cockatoo is ranked as Endangered using the IUCN (2012) Red List Categories and Criteria, meeting Criterion A (1abc) as it has suffered a population decline of at least 50% over the past three generations or 45 years. Based on spatial data analysis, the extent of suitable habitat in the known range of Carnaby's cockatoo (Murchison – Esperance) is estimated at around 1.7 million hectares. This is a 45% reduction in available feeding, breeding and roosting sites in relation to an estimated pre-European figure of 3.8 million hectares (E. Rice, DEC GIS, pers. comm. April 4 2010). Based on the Perth coastal plain IBRA sub-bioregion, the Swan coastal plain, the pre-European vegetation extent in this area accounted for 1.1 million hectares of the estimated suitable habitat known for the birds', with the current extent of vegetation in this area having been reduced by 43% to under 474 000 ha (J. Kinloch, DEC GIS, pers. comm. October).

The loss of breeding, feeding and roosting habitats and the reduction in quality of foraging resources in the remaining habitat are key factors contributing to population declines and range contractions for the species (Saunders 1980, 1990; Berry & Owen 2010). Carnaby's cockatoo decline has previously been attributed to the loss of feeding habitat in the breeding zone, in particular the wheatbelt, where some breeding pairs in some locations are unable to fledge chicks due to inadequate food resources (Saunders 1980, 1990). However, a decline in food resource availability in the non-breeding season is also believed to be contributing to a reduction in numbers (Berry & Owen 2010). Berry and Owen (2010) suggested that breeding success is dependent on the level of body condition acquired during the non-breeding season and the quality and abundance of food resources across feeding habitats on the Swan coastal plain are likely to be major factors in sustaining that part of the population using the Swan coastal plain.

Knowledge about diet is essential for understanding the resources required by a species in order to identify critical habitats, reveal overlap with anthropocentric impacts and guide management decisions regarding threatened species (Saunders 1980, 1990). Food availability studies contribute to our understanding of population and community level consequences when considering limitations of food resources (Hutto

1990). Understanding a species' foraging decisions based on habitat characteristics (e.g. relative plant size), food abundance and profitability of different food resources helps identify and manage suitable habitat for that species.

Limited information is available about factors that influence the size of the Carnaby's cockatoo population, especially in terms of food availability and carrying capacity of remnant vegetation. Studies on food resource availability, in particular the influence of soil type and fire, have been conducted by Valentine and Stock (2008) as part of the Gnangara Sustainability Study. Valentine and Stock (2008) investigated the reproductive output of *B. attenuata* and *Pinus* spp. through a literature review, and utilised Cooper *et al.* (2002) findings on metabolic ecology and seed energy content to estimate the potential carrying capacity of Carnaby's cockatoo in *P. pinaster* plantations and *B. attenuata* woodlands. Despite determining potential food availability estimates, the analysis did not account for handling times, wastage during feeding, tree density, provision of food from other food resources and variation in productivity due to external factors. Understanding the food resource availability across the Swan coastal plain for Carnaby's cockatoo and determining whether resources can support current and future cockatoo populations is crucial for the successful conservation of this species.

Whilst there have been a number of scientific studies on Carnaby's cockatoos, from across its range, there is still much to discover regarding this gregarious species. The aims and objectives of this thesis are to make a significant contribution to existing information, in order to facilitate continued monitoring, habitat assessment and conservation management of the species.

The primary objectives of my study are to:

Objective 1: Determine Carnaby's cockatoo food preferences in proteaceous woodlands on the Swan coastal plain;

Objective 2: Determine food resource availability and the influence of different soil types, time since last fire, presence of disease (*Phytophthora cinnamomi)*, habitat structure and seasonality;

Objective 3: Determine the percentage of available food consumed (availability compared to actual consumption);

Objective 4: Investigate food resource energetics and the amount of food required to meet daily metabolic needs; and

Objective 5: Develop a habitat assessment protocol to quantify the relative quality of remnant food resource habitat.

Chapter 2: Study System

2.1 Carnaby's cockatoo

Carnaby's cockatoo *Calyptorhynchus latirostris* is one of three *Calyptorhynchus* species that occur in Western Australia (Johnstone & Storr 1998). It is endemic to the south west of Western Australia. Carnaby's cockatoo is a large bird ranging from 53-58 cm in length (Johnstone & Storr 1998), weighing between 520 – 790 g (Higgins 1999). It has a black body with a white patch on each cheek and broad white subterminal bands on the tail feathers (Higgins 1999) (Figure 2.1.1). Males and females are easily distinguished from one another as the males have pink eye-rings and a black bill, whereas the females have black-grey eye-rings with a light grey bill and more conspicuous check patches (Higgins 1999).

a b

Figure 2.1.1: Carnaby's cockatoo: a) male and b) female (from Johnstone and Storr 1998).

Carnaby's cockatoo occurs in areas receiving more than 300 mm of rainfall annually (Saunders 1974), ranging from the Murchison to Esperance (Figure 2.1.2) (Johnstone & Storr 1998). Breeding primarily occurs in areas receiving 350-700mm annual rainfall (Saunders 1974), between July to January (Saunders 1980, 1990). Carnaby's cockatoo has undergone a 30% range reduction (Saunders & Ingram 1995), contracting westward and southward of its former range (Saunders 1990; Johnstone *et al.* 2003). This contraction has seen an increase in breeding outside the historical breeding range including locations on the Swan coastal plain such as Yanchep National Park, Yalgorup and Bunbury (Johnstone *et al*. 2003) (Figure 2.1.3).

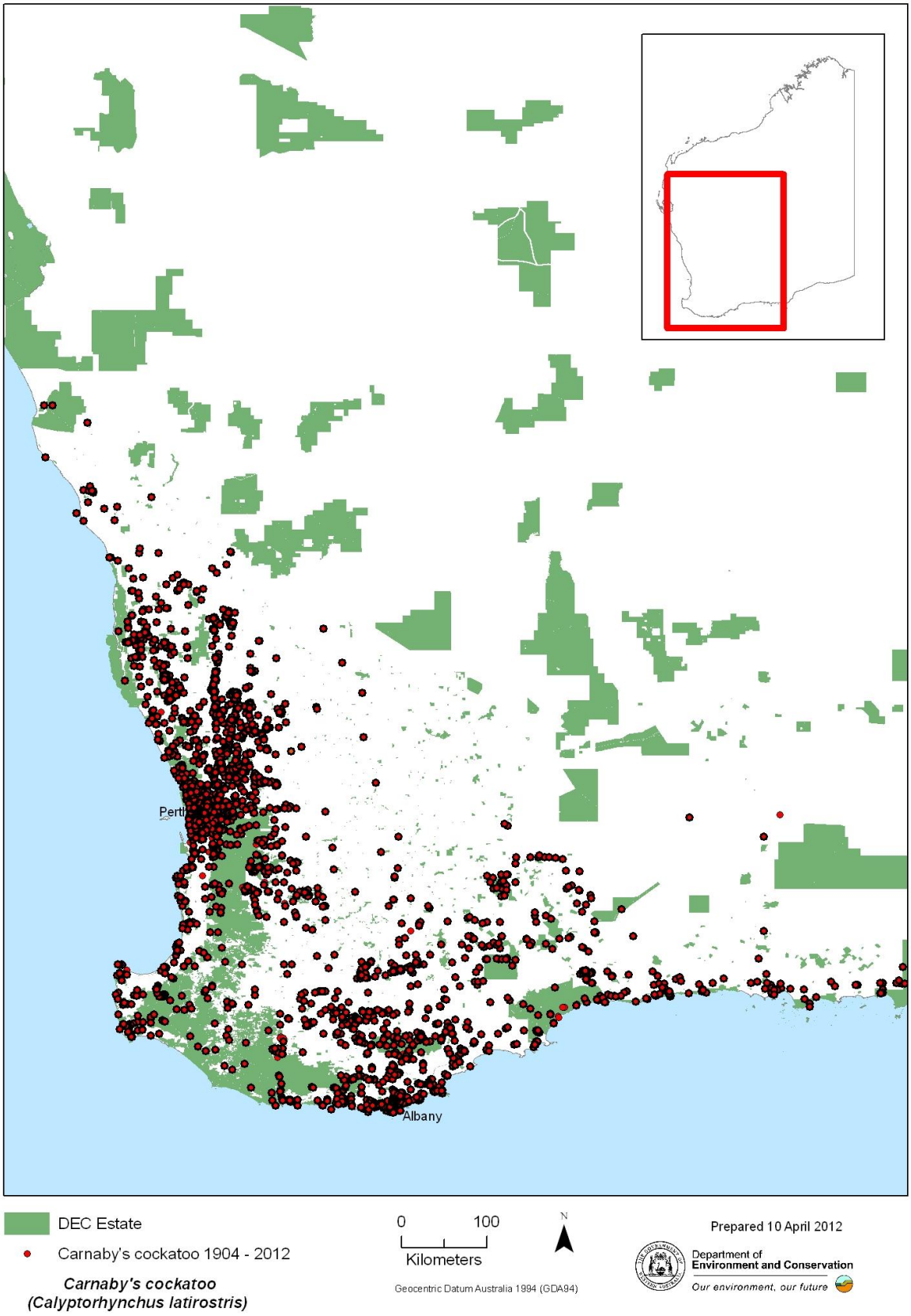


Figure 2.1.2: Carnaby's cockatoo distribution based on reported sightings (1904-2012) (DEC 2012).

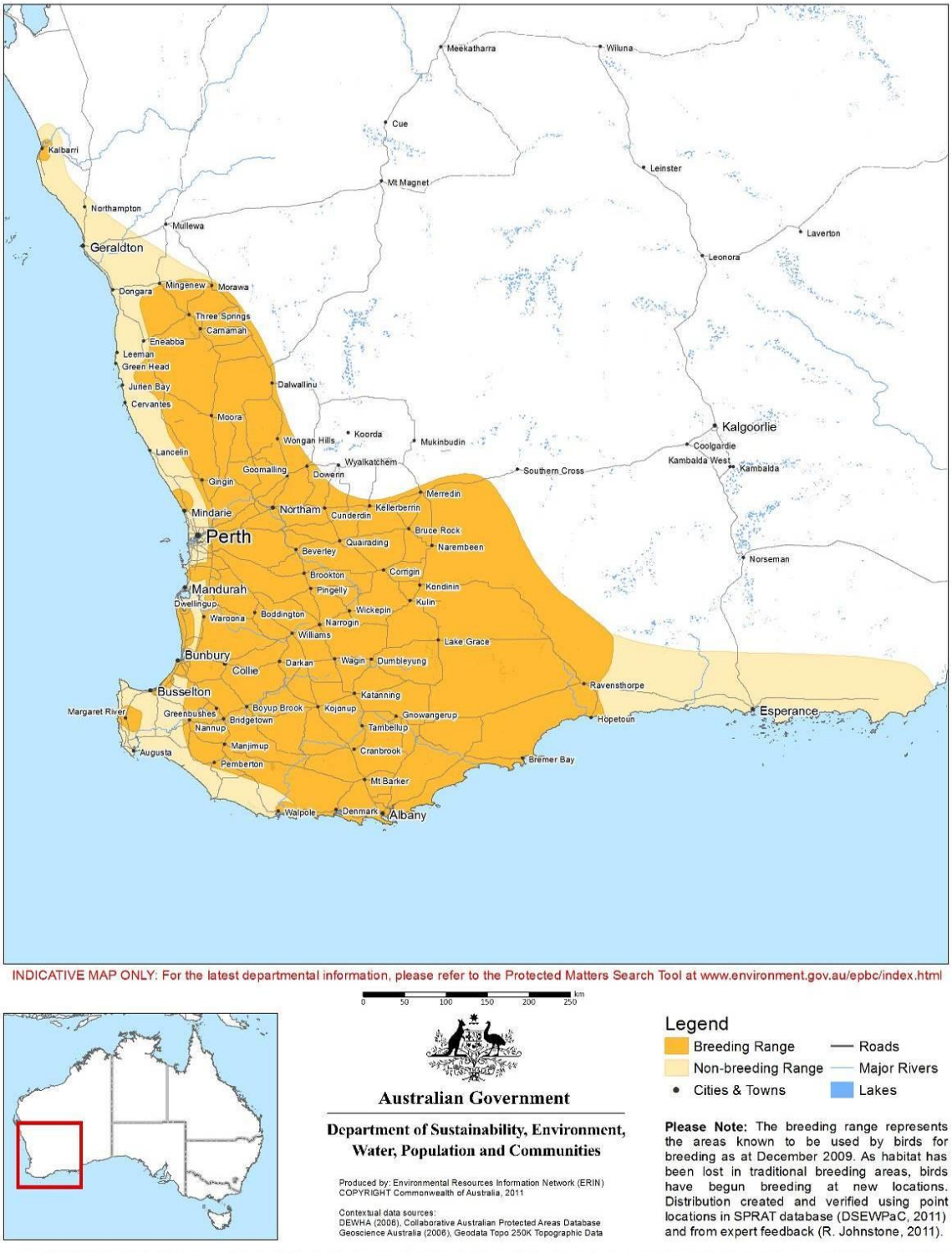


Figure 2.1.3: Breeding and roosting habitat of Carnaby's cockatoo (SEWPAC 2012).

Carnaby's cockatoo typically nests in eucalypt woodlands, primarily in hollows of Wandoo (*Eucalyptus wandoo*) and Salmon Gum (*E. salmonophloia*) in the wheatbelt (Saunders 1979a), and Tuart (*E. gomphocephala*) in coastal areas (Johnstone & Storr 1998). One or two eggs are laid each year, with only one usually being successfully reared (Saunders 1982). Following breeding, Carnaby's cockatoo typically aggregate in large flocks in higher rainfall coastal areas, in search of food (Saunders 1980).

Adult Carnaby's cockatoos have few natural predators, with the exception of the Wedge-tailed eagle (*Aquila audux)* (Saunders & Ingram 1998; Saunders 2002). Nesting chicks are vulnerable to predation by feral cats (*Felis catus*), monitors (*Varanus* spp.), possums (*Trichosurus vulpecula*) and snakes (e.g. *Morelia spilota imbricata*) (Johnstone & Storr, 1998; Dawson *et al.* 2011). Recent trends in adult and juvenile mortality have been attributed to anthropocentric causes, with a significant increase in gun shot and road strike deaths (Saunders 1990; Saunders *et al.* 2011).

Carnaby's cockatoo, like most species, are susceptible to catastrophic and unpredictable climatic events. Deaths have been associated with hailstorms, heat stress and fire (Saunders *et al.* 2011). In March 2010, a hail storm in the Perth metropolitan suburbs resulted in the death of 36 and injury of 20 Carnaby's cockatoos. This event also defoliated key food resource habitat in the worst affected areas. These catastrophic mortality events can lead to significant changes to the local population which may subsequently result in a decline in recruitment (Saunders *et al.* 2011).

The Carnaby's cockatoo population has been estimated at 11 000 – 60 000 birds (Saunders *et al.* 1985). This is the only population estimate published and is over 20 years old which may not correlate with current population trends. However, the current population is believed to be around 40 000 birds (P. Mawson, pers. comm., 2010*)*. Birds Australia WA surveys carried out during April 2010 to April 2011 using specific night time roosts, 'The Great Cocky Count', estimated the non-breeding greater Perth region population to be at least 3 100 to 5 100 (Burnham *et al.* 2010).

Carnaby's cockatoo forage on a diverse array of feeding resources both native and exotic, consisting of 130 plant species from 21 families (Groom 2010). Food items including seed, nectar and insect larvae are consumed (Saunders 1980; Saunders *et al.* 1985; Higgins 1999). On the Swan coastal plain, Carnaby's cockatoo primarily forages in proteaceous woodland, kwongan heath dominated by proteaceous species, commercial pine plantations dominated by *Pinus pinaster* and less frequently in eucalypt forest (Saunders 1980).

Banksia, Corymbia, Eucalyptus, Grevillea, Hakea and *Pinus* seeds constitute 70% of the birds' diet (Valentine and Stock, 2008). Exotic plant species such as *P. pinaster* have become a major seasonal dietary component (Valentine and Stock 2008). Significant native food resource plants on the Swan coastal plain include *Banksia attenuata, B, menziesii, B. sessilis, Corymbia calophylla* and *Eucalyptus marginata* (Groom 2010).

2.2 *Banksia*

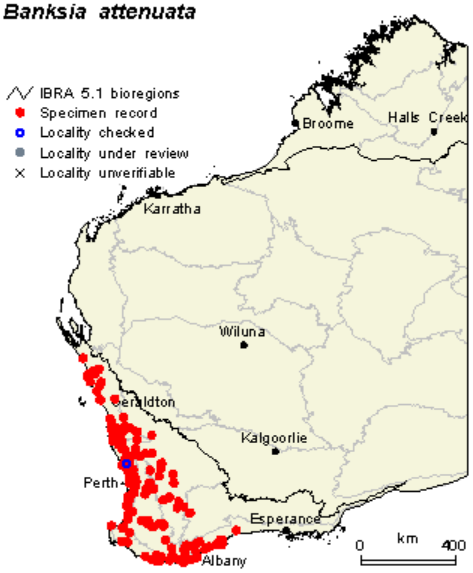
The genus *Banksia* is distributed across the South Western Province and eastern and northern coastal margins of Australia, with one species occurring outside of Australia (Mast 1998). As a result *Banksia* forms a characteristic genus in the South Western Province of Australia (Speck 1958), in which the greatest concentration (George, 1984) and endemism (Lamont & Connell, 1996) of the species exists. The genus *Banksia* today incorporates the species from the formerly named genus *Dryandra*, as a result of phylogenetic work inferred from DNA analysis (Mast 1998; Mast & Givnish 2002; Mast *et al.* 2005; Mast & Thiele 2007). The taxonomic change of *Dryandra* has increased the endemism and dominance of *Banksia* species in the South-west Botanical Province. *Banksia* species provide seed and nectar food resources for a variety of birds (Whelan & Burbidge 1980; Saunders 1980; Shah 2006; Valentine & Stock 2008), invertebrates (Clifford and Drake 1981, Scott & Black 1981) and mammals (Rourke & Wiens 1977; Carpenter 1978). Insects attracted to *Banksia* inflorescences and woody structures are also fed on by a range of animals (Whelan & Burbidge 1980; Scott & Black 1981; van Leeuwen & Lamont 1996).

Proteaceous species contribute over half of the Carnaby's cockatoo diet of which 95% is attributed to *Banksia, Grevillea* and *Hakea* species (Groom 2010). In particular *Banksia* species form a characteristic component of the birds' diet (Saunders 1980: Shah 2006; Valentine & Stock 2008). Fifty-three *Banksia* species occur within the Perth IBRA sub-region and are dominant in most floristic communities on the Swan coastal plain (Western Australian Herbarium 1998-2011). Due to the variety of *Banksia* species and their alternate flowering and fruit maturation periods, banksias form an important dietary component for Carnaby's cockatoo. In particular, *B. attenuata, B. grandis, B. ilicifolia, B. menziesii, B. prionotes* and *B. sessilis* have been identified as important Banksia food plants on the Swan Coastal Plain (Saunders 1980; Shah 2006; Valentine & Stock, 2008). Carnaby's cockatoos feed on all three food resources provided directly and indirectly by *Banksia* species (seed, nectar and insects), which make this genus highly valued (Saunders 1980: Shah 2006; Valentine & Stock 2008). However, the value of each *Banksia* species as a food source for Carnaby's cockatoos is unknown.

Banksia woodlands occur on nutrient poor (Semeniuk & Glassford 1989), well-drained deep sandy soils, which include the Swan coastal plain and Dandaragan Plateau (Beard 1989). Banksia woodlands have been studied extensively in the northern (Eneabba, Watheroo) and southern (Hopetoun) scrub-heath in Western Australian, with studies on their serotiny, fire ecology, productivity and distribution (e.g. Lamont & Baker 1988; Enright & Lamont 1989; Witkowski *et al.* 1991; Lamont *et al.* 1999). However, research on *Banksia* species surrounding the Perth metropolitan and greater Perth area of the Swan coastal plain has been more limited. To increase the knowledge of Banksia woodlands on the Swan coastal plain, *B. attenuata, B. grandis, B. ilicifolia, B. menziesii, B. prionotes* and *B. sessilis* have been identified as the focus of this study.

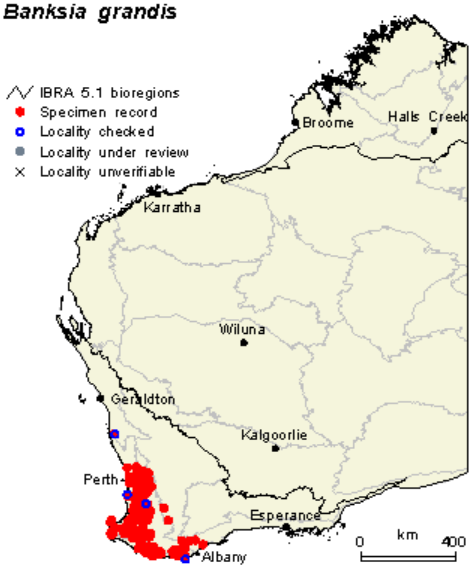
The morphology, abundance and distribution of *Banksia* species varies significantly across the Swan coastal plain (Figures 2.2.1 – 2.2.6). *B. attenuata* and *B. menziesii* form the most common banksia woodland plants on the Swan coastal plain (Taylor and Hopper, 1988) and often coexist in open woodlands with a well-developed mixed shrub understory. In contrast, *B. prionotes* and *B. sessilis* commonly occur in pure stands, while *B. grandis* and *B. ilicifolia* are less common and occur scattered across the Swan coastal plain, with *B. ilicifolia* typically found lower in the landscape where soil moisture is more readily available (Canham *et al.* 2008). Banksias are woody, evergreen plants, ranging from prostrate shrubs to tall trees. The tree form usually has a single trunk while the shrub form is often multi stemmed. Leaf morphology varies greatly, commonly being hard and leathery and prominently toothed or lobed. *Banksia* species characteristically have flower spikes (inflorescences) made up of hundreds to thousands of tiny individual flowers grouped together. Flower colour varies, ranging from red to yellow. The majority of species flower during autumn and winter, however some species, such as *B. attenuata,* flower during summer (Table 2.2.1). Banksia seed primarily forms in cone-like structures called infructescences with grouped hard woody fruits called follicles. The number of follicles per infructescence ranges from one to over 100 depending on the species and often require fire and/or a long period of drying for seed to be released (George 1984). Plant descriptions and phenology of the study species are provided in Table 2.2.1.

Banksia attenuata



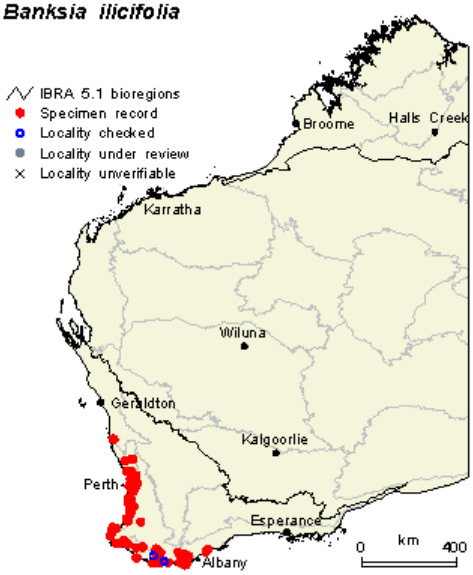
Map by Paul Gioia, WA Herbarium. Current at August 04, 2011

Banksia grandis

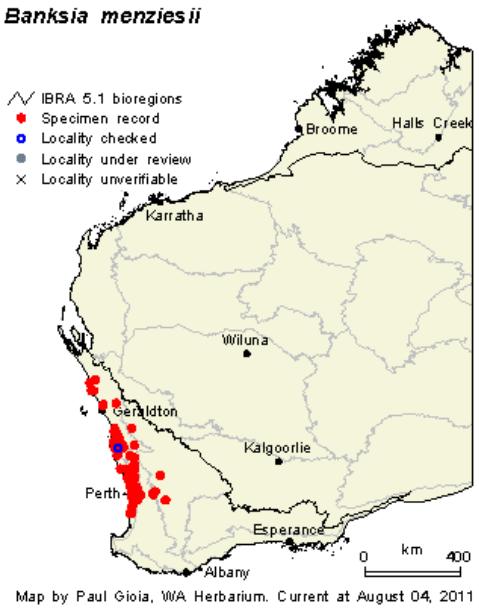


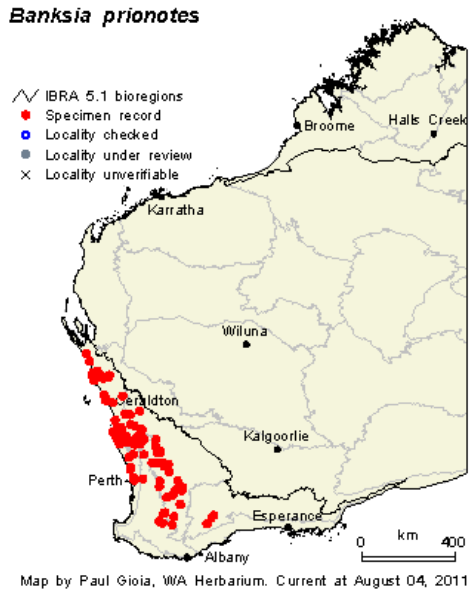
Map by Paul Gioia, WA Herbarium. Current at August 04, 2011

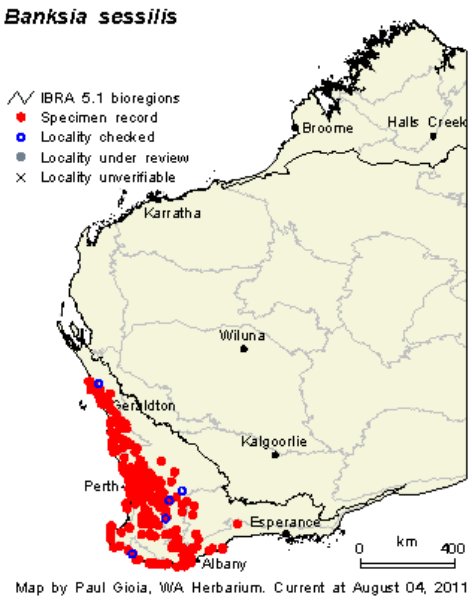
Banksia ilicifolia



Map by Paul Gioia, WA Herbarium. Current at August 04, 2011







Figures 2.2.1–2.2.6: Distribution maps (Western Australian Herbarium 1998-2011) and images of targeted *Banksia* species**.**

Table 2.2.1: *Banksia* species description and phenology**.** Main flowering period highlighted by darker shading.

Scientific Name	Common Name	Brief Description	Flowering													Seed maturation (months)
			J	F	M	A	M	J	J	A	S	O	N	D	*Ref*	
B. attenuata	Slender Banksia	Shrub or tree 2-10m. Leaves broadly linear, truncate, 4-27cm long, 5-16mm wide at flowering. Inflorescence conspicuous, cylindrical, 5-26cm long, 3.5-5cm wide at flowering. Flowers bright yellow.[2]													1,2	12-17 [5]
B. grandis	Bull Banksia	Tree to 10m. Leaves obovate-cuneate, truncate, 10-45cm long, 3-11cm wide. Inflorescence cylindrical, 10-40cm long, 7-9cm wide at flowering. Flowers pale yellow.[2]													1,2,3	12-14 [6,7]
B. ilicifolia	Holly-leaved Banksia	Tree to 10m. Leaves obovate-elliptic, undulate, truncate or obtuse mucronate, 3-10cm long. Inflorescence on short branchlets, head-like, 7-9cm wide. Flowers cream and pink.[2]													1,2	<3 [8]
B. menziesii	Firewood Banksia	Shrub or tree 3-10m. Leaves oblong, truncate, 8-25cm long, 1-4cm wide. Inflorescence ovoid-cylindrical, 4-12cm long, 7-8cm wide at flowering. Flowers deep pink, red and/or yellow.[2]													1,2	unknown
B. prionotes	Acorn Banksia	Shrub or tree to 10m. Leaves broadly linear, obtuse, 15-27cm long, 1-2cm wide. Inflorescence conspicuous, ovoid, 7-15cm long, 7-8cm wide at flowering. Flowers cream and orange.[2]													1	unknown
B. sessilis	Parrot Bush	Shrub 0.8-5m. Leaves cuneate-obovate, obtuse or acute, pungent, 1-4cm long, 5-20mm wide. Inflorescence head-like, 2-4cm wide. Flowers cream-yellow.[3]													4	unknown

References: [1]Whelan and Burbidge 1980; [2]George 1984; [3]Marchant *et al.* 1987; [4]Collins *et al.* 2008; [5]Stock *et al.* 1991; [6]Scott 1982; [7]Abbott 1985.

2.3 Limitations on Food Resource Availability

Disturbance is an integral part of every ecosystem, shaping the spatial and temporal availability/productivity of resources, water cycling and biodiversity heterogeneity of systems (Walker, 2011). The severity and frequency of disturbance impacts on the environment in a predictable manner, altering ecosystem structure and function (Walker, 2011). Understanding these responses/interactions can help manage and protect threatened species. For example, understanding the reproductive and productivity response of *Banksia* species to fire and susceptibility to disease (e.g. *Phytophthora cinnamomi*) can help determine the amount of food resources likely to be available. It is useful to determine the predicted productivity output of banksia woodlands in response to different variables such as soil type, fire age, disease susceptibility and climate, in order to establish the minimum amount of food resources required to sustain that proportion of the Carnaby's cockatoo population that utilises the Swan coastal plain.

Fire

Western Australia's vegetation has evolved to persist with fire, which is integral for maintaining biodiversity (Burrows 2008). Proteaceous vegetation community assemblage and productivity is determined by the frequency and intensity of fire (Lamont *et al.* 1999). Fire plays an important role in shaping the structure and composition of banksia woodlands (Enright & Lamont 1989; Lamont & Baker 1988; Lamont *et al.* 1999; Witkowski *et al.* 1991). *Banksia* species have developed different methods of coping with fire and are broadly categorized into two groups, resprouters and obligate seeders. Obligate seeders rely on germination of seed for survival after fire (Gill & Bradstock 1992), whereas resprouters can reproduce by seed and concealed buds which shoot after disturbances such as fire or drought (Keeley 1986). To ensure replacement, obligate reseeders require a minimum fire-free period after germination for seed production to commence (Lamont & Markey, 1995). Reseeders take three to five years to first fruiting (Cowling *et al.* 1987; Lamont and Barker 1988; Pate *et al.* 1990; Witkowski *et al.* 1991), growing faster than resprouters (Pate *et al.* 1990). Although resprouters are able to regenerate from epicormic buds, a critical size has to be reached (Keeley 1986; Lamont & Markey 1995). Mature plants that resprout after fire can resume flowering within one to three years after fire (Lamont & van Leeuwen 1988; Lamont & Markey 1995, Lamont *et al.* 2007), however some species are less tolerant of fire than others (Lamont & van Leeuwen 1988) taking longer to recover after fire. In exceptional cases seedlings of resprouting species can take 20-30 years to reach flowering (Abbott 1985; Lamont & van Leeuwen 1988). Due to these

biological differences fire is likely to have an impact on food resource availability. The reproductive responses of the study species to fire are described below (Table 2.3.1).

Table 2.3.1: Study species reproductive response to fire

Species	Fire Response	Fire comparisons between study species
B. attenuata	Resprouter[1]	*B. attenuata* can resprout after fire once they have reached 5 years of age, while other resprouters become tolerant once they start flowering[2]. *B. menziesii* is less tolerant of fire than *B. attenuata*[2]. Seedlings of *B. grandis* require >18 years to reach first fruiting[3].
B. grandis	Resprouter[1]	
B. ilicifolia	Resprouter[1]	
B. menziesii	Resprouter[1]	
B. prionotes	Obligate reseeder[4]	*B. prionotes* is usually killed by fire but has a stronger degree of serotiny than *B. sessilis*[6].
B. sessilis	Obligate reseeder[5]	

References: [1]Lamont & Markey 1995; [2] Lamont & van Leeuwen 1988; [3]Abbott 1985; [4]George 1984; [5]Lamont *et al.* 1999; [6]Cowling *et al.* 1987.

Disease

Banksia species do not tolerate disease as well as they do fire. Diseases such as the soil dwelling pathogen, *P. cinnamomi* (dieback), cause irreversible damage to native plant communities altering the diversity, productivity and ecological processes (Shearer & Hill 1989; Shearer & Dillon 1996b). *Phytophthora* was identified by Shearer and Hill (1989) to be the most frequent cause of plant death (73%) reported in publications analysed (Shearer & Hill 1989). Proteaceous species are highly susceptible to *P. cinnamomi* (Shearer & Hill 1989; Shearer & Dillon 1996b), therefore the disease can have a significant negative impact on important food resources for Carnaby's cockatoo (Table 2.3.2).

Table 2.3.2: Study plant susceptibility to *P. cinnamomi*.

Species	***P. cinnamomi* susceptibility****
B. attenuata	50-75% deaths; moderately susceptible
B. grandis	50-75% deaths; moderately susceptible
B. ilicifolia	75-100% deaths; highly susceptible
B. menziesii	50-75% deaths; moderately susceptible
B. prionotes	*75*-100% deaths; highly susceptible
B. sessilis	75-100% deaths; highly susceptible

** C. Dunne, pers. comm., February 4, 2010.

Plant susceptibility to *P. cinnamomi*, as determined by laboratory trials, is not a true reflection of the likely impact in the wild. Despite the presence of dieback disease in a number of banksia woodlands, the disease is often patchy with islands of vegetation persisting. There is a strong correlation between disease centres and geomorphic elements, with 50% of disease centres on the Swan coastal plain associated with the Bassendean Dune System (Shearer and Dillon 1996a). Few disease centres are found

on the soils of the Spearwood and Quindalup Dune Systems (Shearer and Dillon 1996a), meaning that species like *B. prionotes* and *B. sessilis* which primarily occur on Spearwood and Quindalup Dune Systems are less affected than the Bassendean Dune species. Dieback is also less common in areas with lower soil moisture content and in elevated parts of the landscape (Shearer and Dillon 1996a).

Climate

The Swan coastal plain typically experiences a mediterranean climate with an annual rainfall of 600-1 000 mm (Beard 1984), peak rainfall occurs from June to August (Figure 2.3.3) (Bureau of Meteorology 2012a). However, since the 1970s the south-west of Western Australia has experienced a significant decline in rainfall (Pitman and Perkins, 2008; IOCO 2002). Surface air temperature has increased by 0.7°C over the past 100 years (Collins *et al.* 2000).

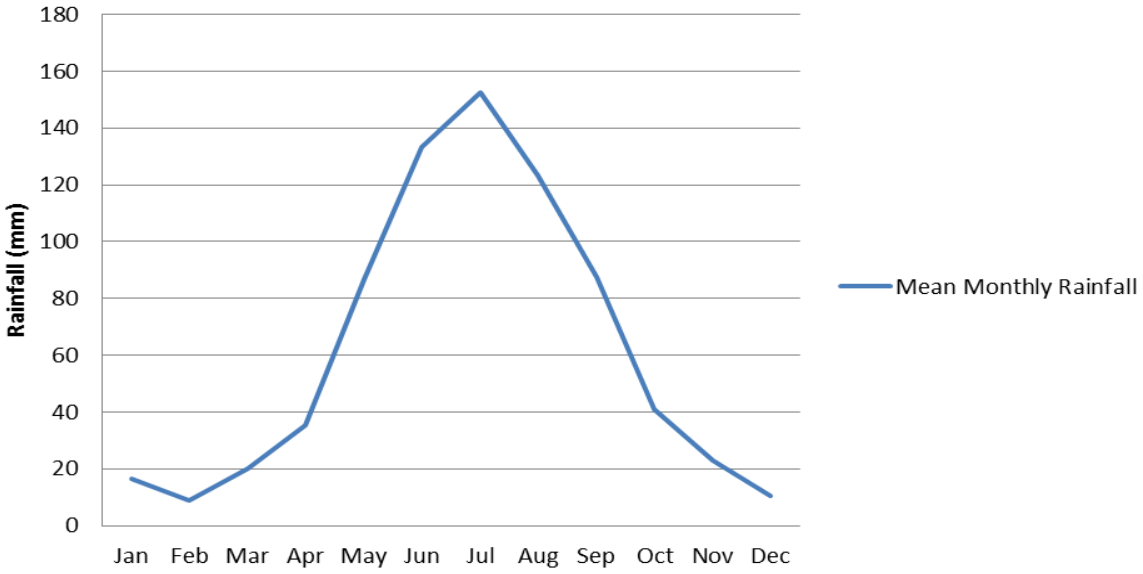


Figure 2.3.3: Perth's mean monthly rainfall (Bureau of Meteorology 2012a)

Climate change is acknowledged to be one of the primary threats to biodiversity and ecosystem function. Over 50% of *Banksia* species in the south-west of Western Australia are predicted to decline under climate change modeling scenarios due to global warming (Fitzpatrick *et al.* 2008). As a consequence of the prediction of reduced rainfall and an increase in temperature, plant communities are likely to change in species composition, distribution, abundance and productivity. The implication of climate change presents a unique challenge for land managers in maintaining a secure food resource for Carnaby's cockatoos into the future.

It is important to note that during the survey period 2010-2011, in which plant data were measured and feeding residues collected, 2010 was the second driest year on record (Bureau of Meteorology 2012b), with 2011 being the wettest year since 2005 (Table 2.3.4) (Bureau of Meteorology 2012b, 2012c). In comparison to average climate conditions, consideration needs to be given to the amount of ecosystem plasticity that can be experienced.

Table 2.3.4: Perth mean rainfall and temperature for 2010 and 2011 (Bureau of Meteorology 2012b, 2012c).

	Average	2010	2011
Mean Rainfall (mm)	**738.5**	**503.8**	**860.8**
Mean max temperature (°C)	**24.6**	**25.3**	**25.7**
Mean min temperature (°C)	**12.7**	**12.4**	**14.0**

2.4 Study area and site locations

The Swan coastal plain forms an important non-breeding feeding ground for Carnaby's cockatoo from December to July (Saunders 1980). Situated on the western edge of Western Australia, the Swan coastal belt as defined by Gentilli and Fairbridge (1951) extends from Geraldton to southwards of Dunsborough, The Swan coastal plain is around 563 km in length and 20-30 km wide (Gentilli & Fairbridge 1951) and is divided into three subregions with the southern section, the Swan coastal plain, confined to south of Muchea (McArthur & Bettenay 1960) (Figure 2.3.1).

The Swan coastal plain is a low lying plain, receiving between 600 and 1 000 mm annual rainfall (Beard 1984). Divided into five geomorphic units the Swan coastal plain consists of Ridge Hill, Pinjarra Plain, Bassendean Dunes, Spearwood Dunes and Quindalup Dunes (McArthur & Bettenay 1960; Semeniuk & Glassford 1989) (Table 2.4.1). Lying relatively parallel to the coast, the plain and dune landforms are characterised by different soil types (Figure 2.4.1). The youngest dune system located on the western edge of the plain is the Quindalup system. These are coastal dunes consisting of calcareous coastal Holocence sands (McArthur & Bettenay 1960). The Quindalup system is followed by the Spearwood Dune system which is characterised by Pleistocene aeolian deposited sands overlaying Tamala Limestone (McArthur & Bettenay 1960). The soil profile of the Spearwood Dunes is less leached than the Bassendean system which consists of undulating hills of heavily leached Pleistocene aeolian sands, forming the oldest dune system (McArthur & Bettenay 1960). Situated to the east of the Swan coastal plain, the Pinjarra Plain is an alluvial plain originating from river systems flowing down from the plateau (McArthur & Bettenay 1960). The eastern

margin of the Swan Coastal Plain is bordered by the Ridge Hill of laterite formation and colluvial sands (McArthur & Bettenay 1960).

Table 2.4.1: Swan coastal plain geomorphic units (McArthur & Bettenay 1960 adapted from Bettenay *et al.* 1960).

	Geomorphic Element				
	Ridge Hill	Pinjarra Plain	Bassendean Dune System	Spearwood Dune System	Quindalup Dune System
Soil association	Forrestfield	Guildford Swan Serpentine River	Southern River Bassendean	Karrakatta Cottesloe Yonngarillup	Quindalup

The Swan coastal plain supports a variety of landuses (Figure 2.4.2). Urban development is largely centred around Perth, radiating out along the coastlines of the Swan and Canning Rivers, Indian Ocean and arterial linkages. Agriculture, including horticulture, forestry, dry land cultivation and animal husbandry, is dominant both north and south of Perth with semi-rural activities being more prevalent in the south. This highly fragmented landscape includes a diversity of remnant bushland areas, ranging from a few hectares to thousands of hectares. Bushland patches are generally smaller with fewer linkages in urban and semi-rural areas with larger continuous expanses of vegetation more common to the north.

With a mediterranean type climate and nutrient poor soils the Swan coastal plain vegetation is characterised by Proteaceous woodlands, eucalyptus forest, and paperbark (*Melaleuca* spp.) woodlands in wetland areas (Heddle *et al.* 1980; Beard 1984; Gibson *et al.* 1994). Banksia woodlands form the dominant vegetation component on the Swan coastal plain, (Heddle *et al.* 1980; Beard 1984; Gibson *et al.* 1994) and are closely associated with the Pinjarra Plain, Bassendean Dunes, Spearwood Dunes and, to a lesser extent, Quindalup Dunes (McArthur and Bettenay 1960). Due to the widespread distribution of *Banksia* species across the Swan coastal plain (Figure 2.4.3) and their significance as a food resource for Carnaby's cockatoo, *Banksia* was chosen as part of this study for further investigation.

A truncated portion of the Swan coastal plain was studied for the purpose of this research, which included the area south of Guilderton (31° 20′ S) to the southern boundary of Waroona Shire (32° 55′ S). This area is bounded by the Indian Ocean to the west and Darling Scarp (116° 02' E) to the east. The study area covers an area of 5 075 km^2, is approximately 170 km in length and 25 km wide. Twenty-one bushland study sites were selected across the Swan coastal plain in banksia-dominated woodlands (Figure 2.4.4). Coastal, wetland and transition vegetation zones were excluded from site selection. The sites comprised a variety of landform types, time since last fire, health conditions and vegetation communities (Refer to Appendix 1, 2 and 3).

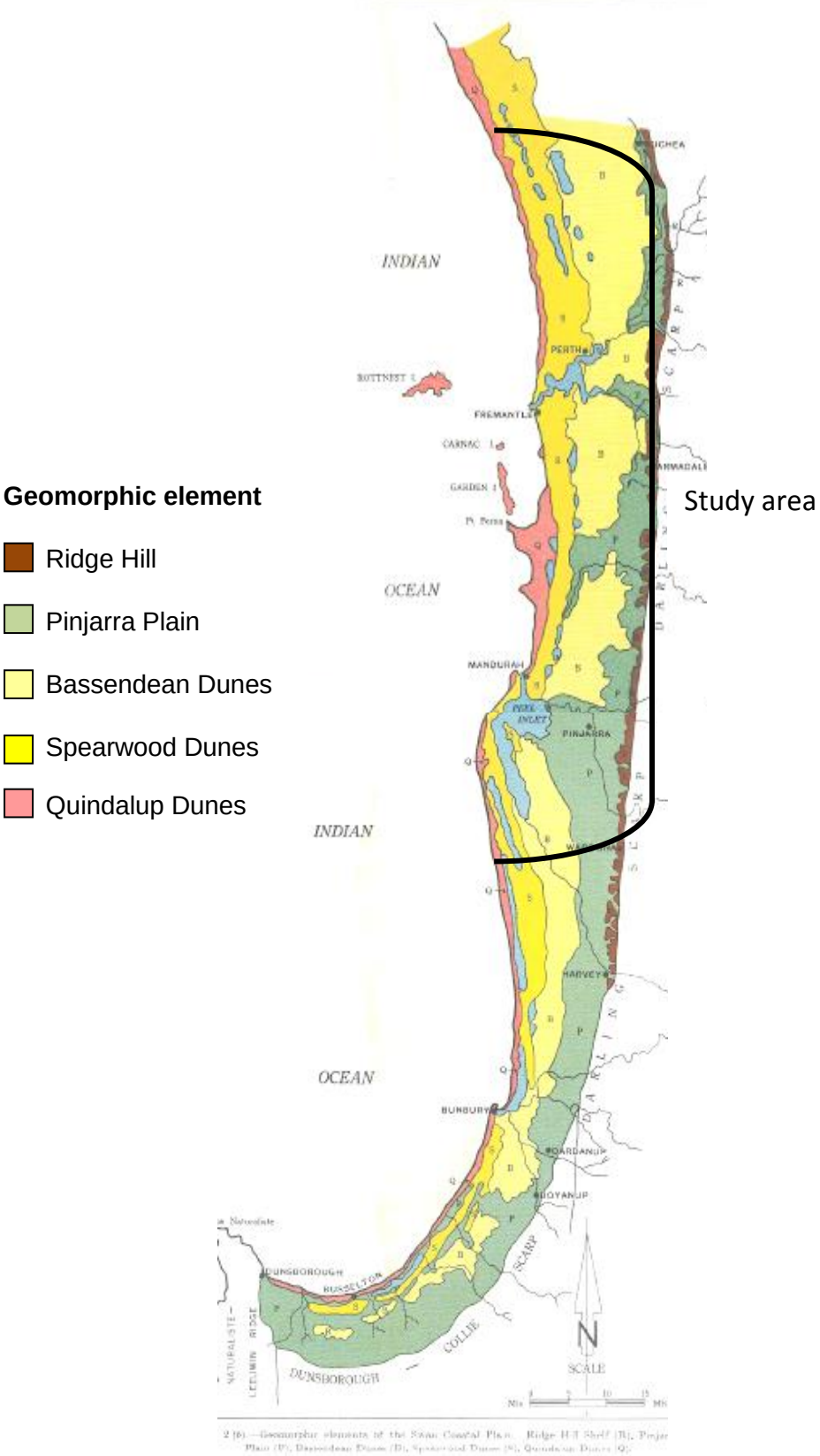


Figure 2.4.1: Geomorphic units of the Swan coastal plain (McArthur & Bettenay 1960).

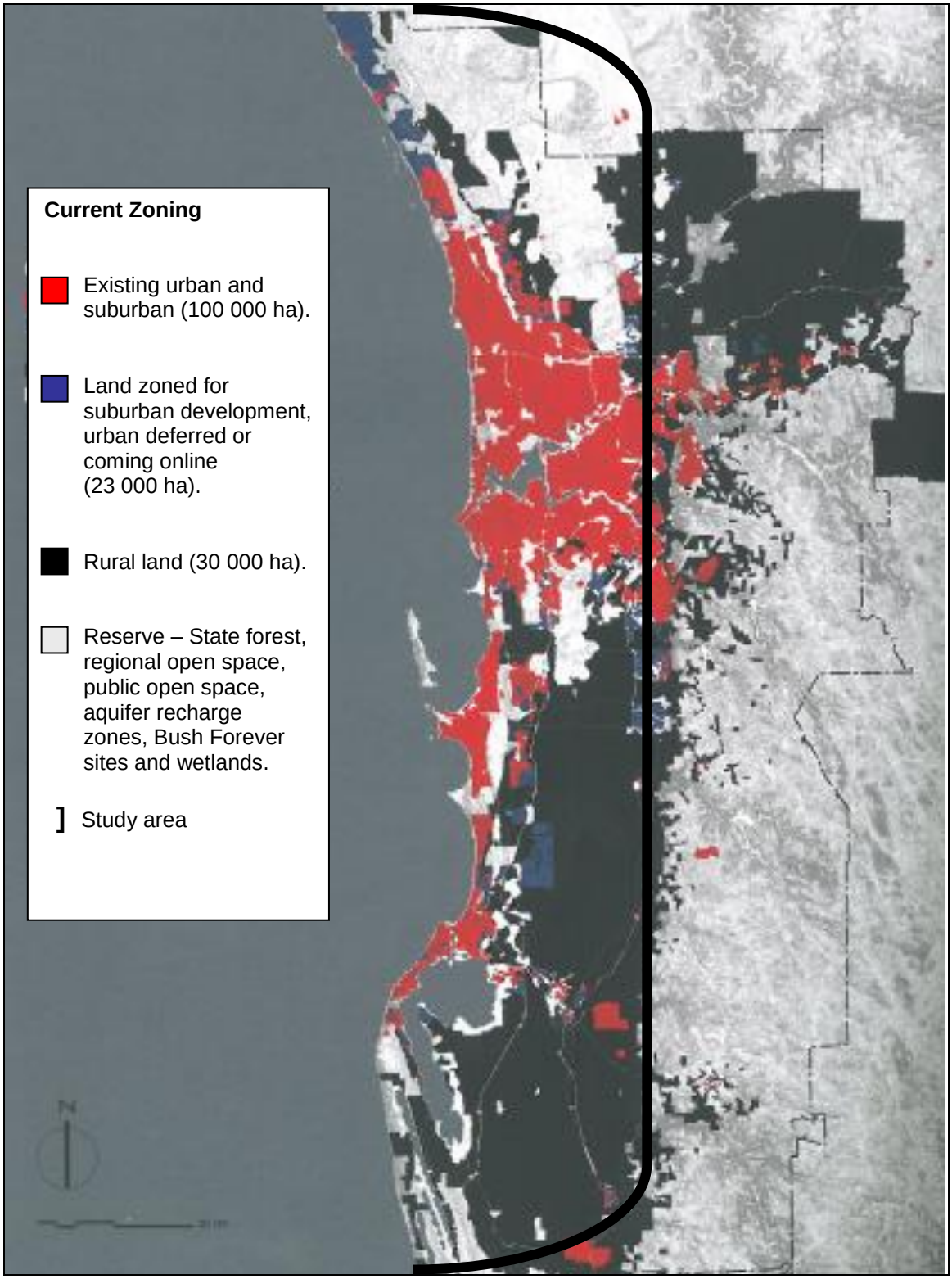


Figure 2.4.2: Major land uses in the study area (Weller 2009).

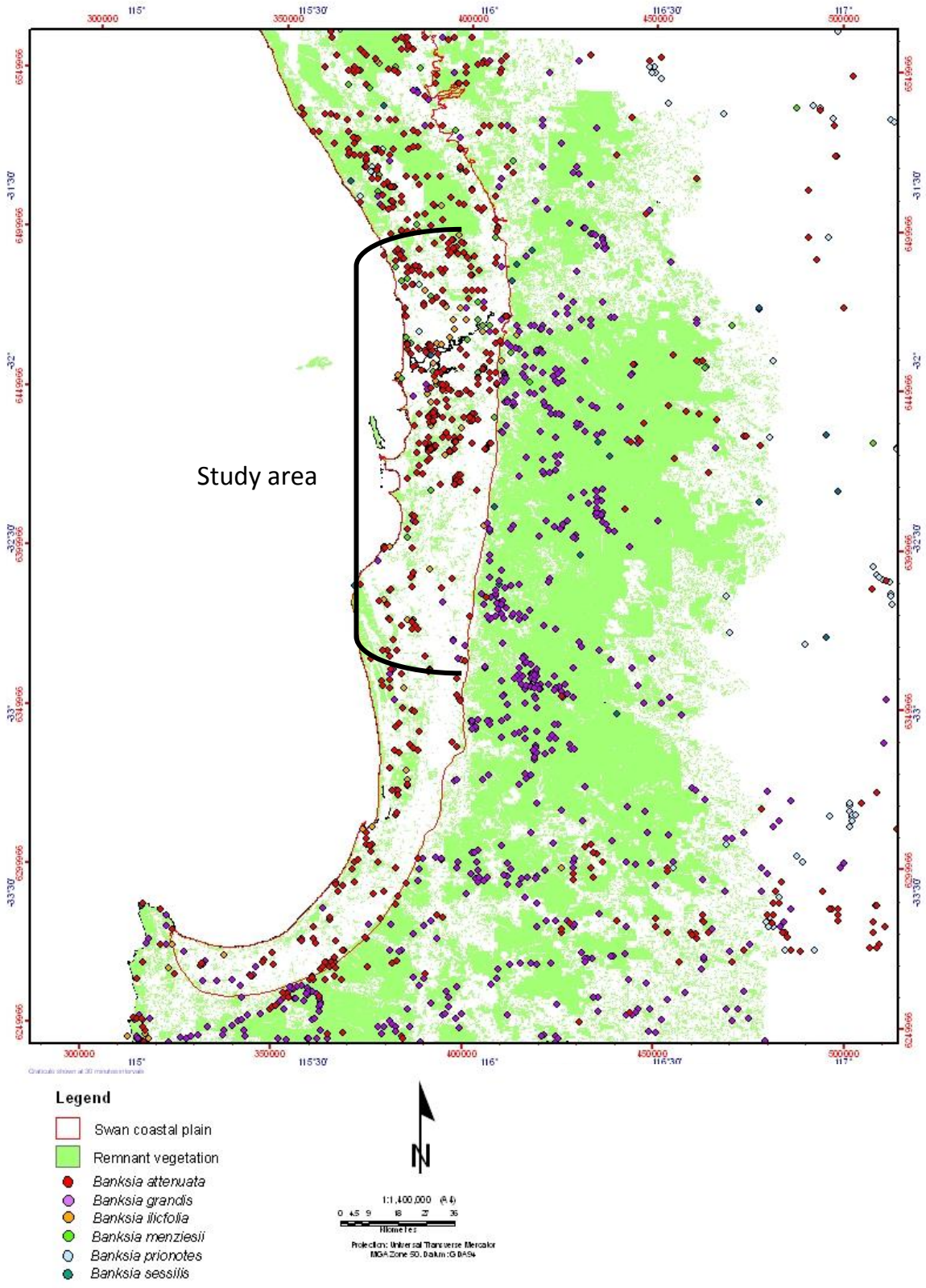


Figure 2.4.3: Distribution of *Banksia* species on the Swan coastal plain and surrounding areas (Western Australian Herbarium 1998-2011)

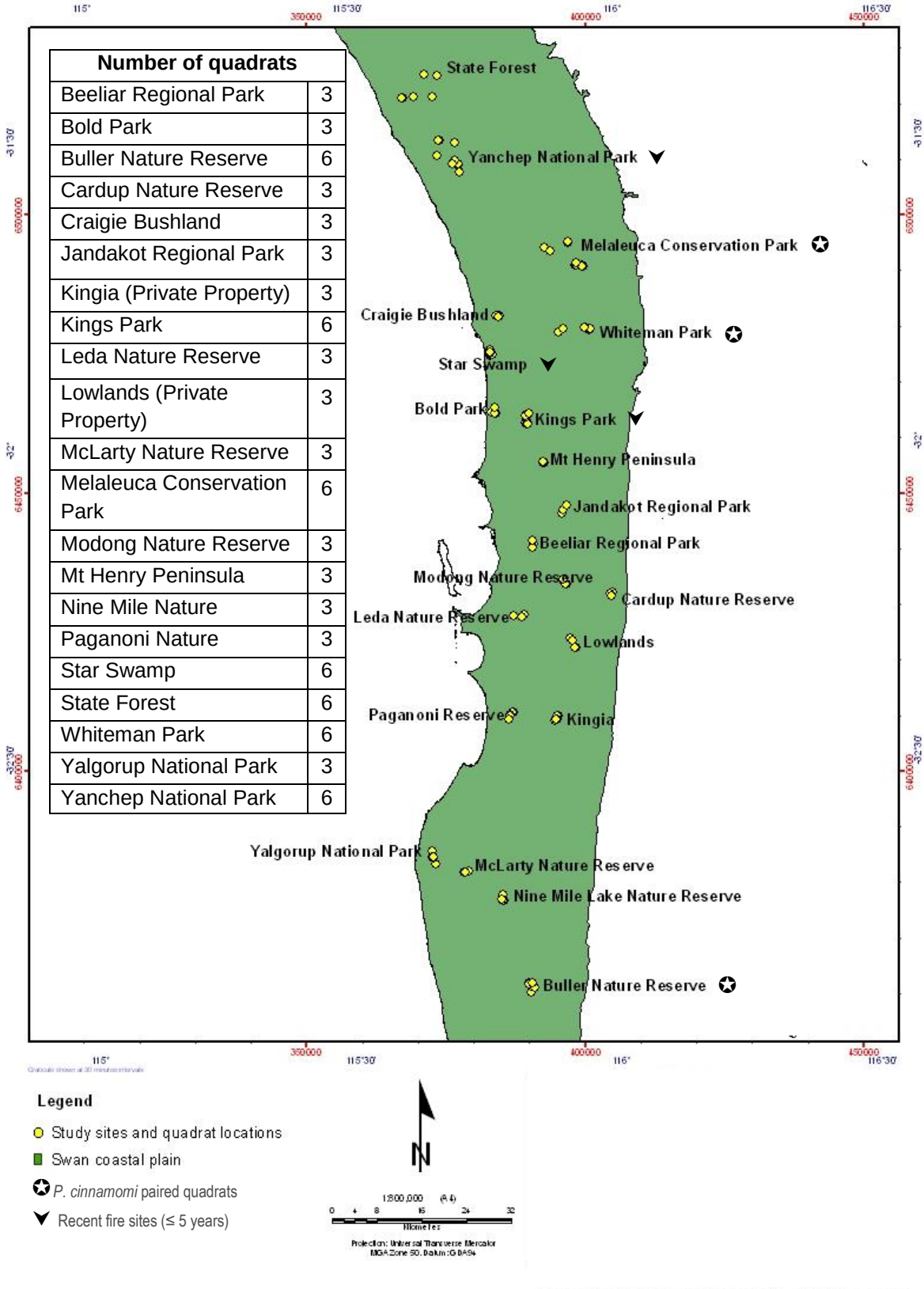


Figure 2.4.4: The distribution of the 21 study sites selected for this study and the number of quadrats in each across the Swan coastal plain.

2.5 Site Selection

This study was undertaken in banksia woodlands across the Swan coastal plain north of Johnston Road, Waroona and south of Gingin Brook Road, Gingin. The entire Swan coastal plain was not studied due to logistics, time and personnel availability. The study area was separated into three zones, northern zone (Guilderton – Reid Highway), central zone (Reid Highway – Mundijong Road) and southern zone (Mundijong Road – the southern border Shire of Waroona). The division of the plain into three zones was to ensure study areas were selected at a variety of different sites across the non-breeding range of Carnaby's cockatoo. Each of the zones display different land use activities; the northern zone contains large areas of intact remnant vegetation. The central zone is highly urbanised with pockets of bush scattered throughout and the southern zone has been cleared for grazing and contains fewer, large continuous patches of remnant vegetation than the northern zone.

Study sites were selected on the basis of *Banksia* species assemblage, soil type, time since last fire, health and accessibility. An even distribution of sites across the major soil systems (Quindalup Dunes, Spearwood Dunes, Bassendean Dunes and Pinjarra Plain) within each zone was contemplated to allow the best possible basis for analysis. However, banksia woodlands on the Quindalup system were difficult to locate therefore only one site was selected. No sites were selected on the Pinjarra Plain due to the highly developed (urban and agriculture) nature of this geomorphic element. Recent fire sites and sites that had been surveyed and identified as *P. cinnamomi* infected were also included in the survey to determine the impact on food availability. Fire sites were only selected on the Bassendean Dune System as there were not enough suitable sites on the Spearwood or Quindalup Dune Systems. The Bassendean Dune Systems has been identified by Shearer and Dillon (1996) as the geomorphic element which contains the most *P. cinnamomi* disease centres on the Swan Coastal Plain.

ArcGIS® was used to assist in the identification of sites with the required soil, fire and disease characteristics that supported local *Banksia* species. Department of Environment and Conservation WA (DEC) data sets were accessed to facilitate preliminary site selection. Soil types were determined by extracting spatial data for each of the study sites. Soil-landscape systems mapping of the south west of Western Australia, Agriculture Western Australia, Version 4 (December 2006) was utilised to assess soil types. Sites were selected across the main landform systems, Quindalup Dunes, Spearwood Dunes and Bassendean Dunes within the study area. However there were few suitable sites on the Quindalup dune system and Pinjarra Plain.

To study the impact fire has on food resource availability, DEC Fuel Age spatial data were utilised to determine year since last fire. Unfortunately, data were scarce and fire boundaries were unreliable for many of the reserves/sites, necessitating ground-truthing at several sites. To assess health, data collected as part of Project Dieback Natural Resource Management (NRM) were utilised to evaluate and assist with site selection to examine food resource availability in diseased areas. Project Dieback NRM was a cross regional initiative delivered by the South Coastal Region NRM Inc., funded by the Australian Government and the Government of Western Australia. The dieback mapping was compiled by the DEC Forest Management Branch.

Quadrats

Utilising maps generated from ArcGIS®, sites were surveyed by foot and vehicle (where permitted and only along tracks) to obtain an overview of banksia distribution and site variation. Quadrats were stratified randomly with regard to landscape position based on topography (crest, slope and swale), where possible. Due to the variability of banksia woodlands, quadrat selection was quite difficult and the selection was based on site tenure, access and terrain.

Due to the issues associated with establishing fire age through desktop analysis, maps were used in conjunction with general observations of the site and the plant age was established through node counts in an attempt to ground truth spatial data, where possible. Node counts involved counting the number of junctions (or nodes) between growth increments (Wills 2003). Vegetation node counts show a strong correlation to banksia age or time since fire (Wills 2003). Property owners and managers of non-DEC managed lands were engaged to assist with fire history information.

Sites that have been, or are currently, infected with *P. cinnamomi* were selected for analysis of food resource availability in diseased areas. Government spatial data sets were accessed in addition to an on-ground assessment to evaluate disease presence. This on-ground assessment was carried out using the Department of Environment and Conservation dieback interpretation techniques (CALM 2001). The assessment involved identifying the presence of plant disease in indicator species, such as loss of foliage, yellowing in leaves, thinning of understory vegetation and the distribution of dead trees. Two soil samples were also collected from each quadrat to identify any current presence of disease. Soil sampling was undertaken randomly unless areas within the quadrat displayed signs of dying or very recently-killed indicator plant species. Soil and root material were collected as per DEC guidelines (CALM 2001). DEC WA disease risk management hygiene standards were adhered to during this

study (CALM 2001). Soil samples were tested by DEC Vegetation Health Services which involved the baiting of samples for presence of *Phytophthora*. Baiting involved placing soil and plant-root material from the sample collected with distilled water and plating on a selective agar medium in a petri dish. *Eucalyptus sieberi* cotyledons were added to the bait and incubated. *Phytophthora* colonies that emerged were then isolated to a pure culture. All cultures were identified to species by DEC Vegetation Health Services technical officers.

At 21 sites, 84 representative quadrats were established. Three quadrats were established for representative sampling of a given site for each soil type, fire age, health condition and woodland community. At six sites multiple condition quadrats were established and analysed (e.g. Whiteman Park had three diseased quadrats and three disease free quadrats; Star Swamp had three recent fire (< 5 years) quadrats and three post-fire quadrats > 5 years). An additional three quadrats were selected north of Yanchep to further investigate *B. sessilis* proteaceous heath. Overall the 84 quadrats consisted of nine *P. cinnamomi* quadrats, nine recent fire quadrats (< 5 years post-fire), nine quadrats 6-10 years post-fire; 15 quadrats 11-15 years post-fire, nine quadrats 16-20 years post-fire and 32 quadrats > 21 years post-fire (Appendix 3).

Quadrat size was set at 20 m x 20 m, consistent with previous research conducted on banksia woodlands (Enright and Lamont 1989; Witkowski *et al.* 1991; Lamont *et al.* 1999). Quadrat size was important as stem density varied across the Swan coastal plain and the size selected needed to be large enough to guarantee banksia plants were captured within quadrats. Square quadrats were established using the hypotenuse method ($c= \sqrt{a^2+b^2}$), whereby a right angled triangle was formed using a hypotenuse of 28.28 m and then mirrored on the other side. Quadrat locations were marked using fence droppers placed in each corner of the quadrat with flagging tape attached. Quadrats were placed parallel to the slope to avoid any changes in vegetation density. Quadrat locations were stored as waypoints in a GPS. For personal safety reasons, and to assist in the establishment of quadrats, volunteers were engaged and completed tasks as per my directions

2.6 Outline of thesis

The chapters in this thesis follow the order of project objectives (pp. 3). Each chapter is presented in a paper format and may contain replicated information (e.g. methods) from other chapters. Chapter descriptions are provided below to guide understanding and to highlight the framework to the study whereby each chapter builds on the previous ones.

Chapter 3, Objective 1: Feeding residues left behind by Carnaby's cockatoos following feeding bouts were analysed to determine food preferences in proteaceous woodlands on the Swan coastal plain. This included the identification of plant species and structures utilised by the birds. Sampling of the feeding residues allowed analyses of the birds' diet to be conducted in the absence of the birds, providing rapid results of feeding activity over a large area whilst reducing animal ethics consideration regarding the human-wildlife conflict.

Chapter 4, Objective 2: The importance of *Banksia* species is further investigated by examining food resource availability and the influence of different soil types, time since last fire, presence of the disease *P. cinnamomi* and seasonality on banksia infructescence numbers. Plant allometric relationships between morphological characteristics and number of infructescences were investigated to help identify factors which best predict number of infructescences. Understanding the predicted response of plants to external factors and relationships to structural and functional plant characteristics is essential in determining the amount of food available for threatened species such as the Carnaby's cockatoo. By identifying key factors, information could be used to reveal important feeding habitats to help manage and conserve the species.

Chapter 5, Objective 3: Banksia infructescence consumption by Carnaby's cockatoos is investigated in comparison to the percentage of infructescences available (Chapter 4). This part of the study quantifies the relationship between infructescence availability and consumption to determine limitations in food resources. Percentage of food consumed is useful in determining whether enough food resources are available to support current populations, helping to highlight the need for habitat protection.

Chapter 6, Objective 4: This chapter further investigates the consumption of banksia infructescence food resources by defining intake at the seed and energetic reward level. Seed energetics and the proportion of seeds and follicles available and consumed were compared to determine the number of infructescences required to meet the daily metabolic requirements of Carnaby's cockatoo. Understanding Carnaby's cockatoo feeding efficiency with respect to metabolic requirements and seed

and follicle resource availability should assist the management of habitats by ensuring sufficient resources are protected.

Chapter 7, Objective 5: This chapter incorporates the findings from Chapters 4, 5 and 6 on infructescence availability, consumption and seed reward through the development of a habitat assessment protocol for evaluating banksia woodland habitat quality for non-breeding Carnaby's cockatoos. This chapter addresses gaps in knowledge and procedures for assessing Carnaby's cockatoo feeding habitat. The development of a method for assessing food resource potential of *Banksia* species aims to assist and strengthen the decision-making processes regarding native vegetation management, whilst also being cost-effective.

Chapter 8: This final chapter synthesises the key findings from this study and discusses the potential management application of the assessment protocol.

Chapter 3: Carnaby's Cockatoo feeding activity in remnant vegetation on the Swan coastal plain

Introduction

Carnaby's cockatoo *Calyptorhynchus latirostris* is endemic to South Western Australia and occurs in areas receiving more than 300 mm mean annual rainfall. The species forages primarily in proteaceous woodland, kwongan heath dominated by proteaceous species, commercial pine plantations dominated by *Pinus pinaster* and less frequently in eucalypt forest (Saunders 1980). Carnaby's cockatoos feed on a diverse array of food resources (Saunders 1980; Valentine & Stock 2008; Groom 2010) which include both native and exotic plants consisting of 130 plant species belonging to 21 families (Groom 2010). Food items consumed include seed, nectar, insect larvae and wood boring insects (Saunders 1979a; Saunders 1980; Saunders *et al.* 1985; Higgins 1999). The diet of Carnaby's cockatoo has recently been shown to consist of a mix of species, with 70% of seed selection attributed to *Banksia, Eucalyptus, Corymbia, Hakea*, *Grevillea* and *Pinus* species (Valentine & Stock 2008). Proteaceous species contribute over half of the known native food species with *Banksia*, *Grevillea* and *Hakea* the most commonly consumed plants (Groom 2010).

Despite our knowledge of Carnaby's cockatoo food sources many feeding records are from the northern section of the coastal plain (north of Wanneroo) (Valentine & Stock 2008), pine plantations (Perry 1948; Serventy 1984; Sedgwick 1955; Saunders 1974; Saunders 1980) and the northern wheatbelt (Saunders 1980). Limited information exists for the central and southern sections of the Swan coastal plain and there are few recent feeding records. Published information mainly consists of single observations of particular plants or invertebrates that have been consumed and the relative contribution made by each species to the total diet is unknown. The seasonal availability and relative quality of each species as a food source is also unknown.

This chapter describes the food resources eaten by Carnaby's cockatoos based on foraging signs recorded from February to December 2011 in remnant vegetation across the Swan coastal plain. Foraging was investigated by examining feeding residues (Valentine & Stock 2008) or chewings (Joseph 1982) of food resource waste material left behind by the birds following feeding bouts. Discarded fruits, cones, infructescences or flowers, chewed twigs and signs of grubbing for insect larvae or insects in woody structures were collected in the field and examined in the laboratory. Due to the highly mobile nature of the birds, feeding residue assessments provide an efficient method of identifying preferred food plants. The aim of this part of the study

was to identify the range of plant species Carnaby's cockatoos used as a food resource on the Swan coastal plain.

Study Sites

This study was undertaken across the Swan coastal plain from south of Guilderton (31° 20' S) to the southern boundary of Waroona Shire (32° 55′ S). The area is bounded by the Indian Ocean to the west and Darling Scarp (116° 02' E) to the east. Situated on the western edge of Australia, the study area covers an area of 5 075 km^2 (approximately 170 km in length and 25 km wide). The Swan coastal plain is a low lying plain dominated by nutrient-poor soils (McArthur & Bettenay 1960) that experiences a mediterranean climate with an annual rainfall of 600-1 000 mm (Beard 1984).

Methods

Study sites were selected across the Swan coastal plain in proteaceous woodlands. Potential sites were selected using spatial data maps generated from geographical information system ArcGIS® (refer to Chapter 2). These were then surveyed to determine their suitability as representatives of banksia woodland. Coastal, wetland and transition vegetation zones were excluded from site selection.

Eighty-four 20 m x 20 m quadrats were established across 21 bushland sites (Figure 3.1). Sites comprised a variety of landform types, vegetation health conditions, time since last fire, and plant communities. Three representative quadrats were established within each of the 21 sites for each selected vegetation health condition, time since last fire or vegetation complex. Quadrats were marked by inserting fence droppers at each corner.

Sites were surveyed bi-monthly from February to December 2011, resulting in six collection periods in total. Each plant species consumed by Carnaby's cockatoos was recorded in each quadrat. Records were made of the number of eaten fruiting structures, uneaten fruiting structures that appeared to have been pruned, pruned green foliage and pruned inflorescences or flowers on the ground. Any fruiting structure that had a mark that appeared to have been made by a Carnaby's cockatoo was classified as eaten, ranging from completely torn apart to structures with only one chew mark present. Grubbing for invertebrates from the woody tissue of branches was also recorded. Uneaten fruiting structures were those that only appeared to have chew marks on the stem with no obvious signs of seed or insect larvae extraction from the structure itself. Structures of plant feeding residues (cones, nuts, infructescence, inflorescences, flowers, twigs) were recorded for all quadrats during each survey

period. Feeding residues were removed from quadrats after each survey to ensure that feeding signs were not recounted in subsequent surveys.

The identity of the bird taxon that had produced the feeding residues / chewings was established by examining bill marks which are species-specific. Forest red-tailed cockatoos severely damage *Corymbia calophylla* (Marri) fruit and seeds are accessed from either the bottom or from the top of the fruit. Carnaby's cockatoos partially or completely removed the rim of *C. calophylla* with indentations all over the fruit, indicating the many bites needed to access seeds. The indentations on fruits made by the lower mandible of Carnaby's cockatoos are 6-7 mm wide and can be differentiated from the Forest red-tailed cockatoo which are slightly wider, 8-9 mm. Feeding traces that could not be assigned to a particular taxon were omitted from the feeding records.

To ensure feeding residue was not missed or overlooked due to dense understorey vegetation, small flags were used to mark out 5 m x 5 m quadrats nested within the 20 m x 20 m quadrat. Each nested quadrat was surveyed systematically, whilst being mindful to minimise disturbance to understorey vegetation. For *B. sessilis* stands an alternative method was used due to the high density of stems and differences in infructescence morphology from other species of *Banksia*. Three 2 m x 2 m nested quadrats were randomly established within the larger 20 m x 20 m quadrat. Two 0.5 m x 0.5 m residue trays were placed in the nested quadrats to collect discarded structures. Two residue trays were also placed in quadrats where density of *B. sessilis* stems was low and the results scaled up by a factor proportional to the total canopy area that *B. sessilis* contributed for that site.

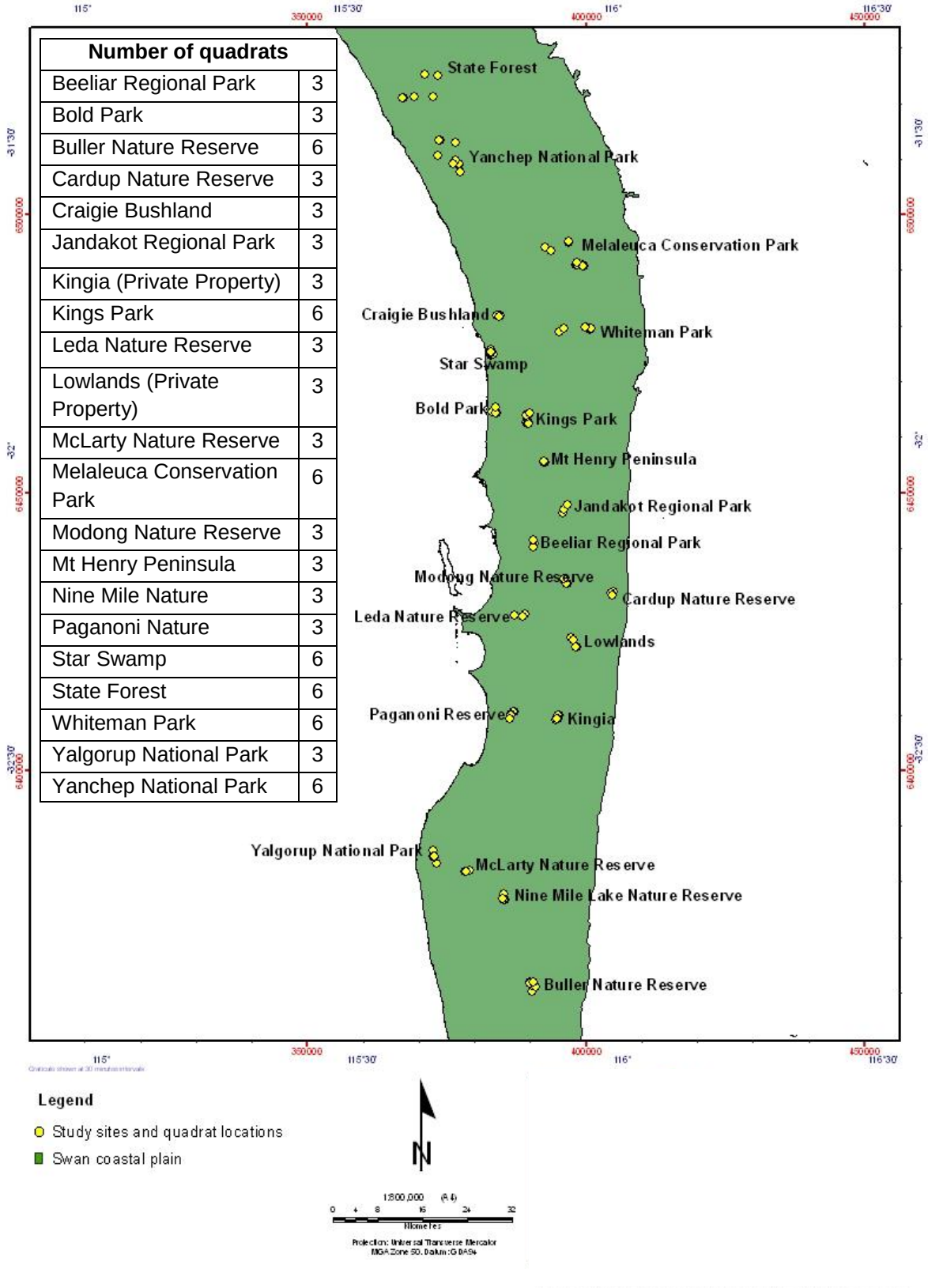


Figure 3.1: The distribution of the 21 study sites selected for this study and the number of quadrats in each across the Swan coastal plain.

Results

Foraging signs by Carnaby's cockatoos were recorded from 24 species of plants in the study area (Table 3.1). Fifteen of the 24 species manipulated were consumed to extract the seeds contained in their fruiting structures. Six of those 15 species (all *Banksia* spp.) were also manipulated as inflorescences, although it could not be determined whether the cockatoos were feeding on the inflorescences in order to extract nectar or to gain access to invertebrates attracted to the nectar. Fifteen species of plants showed evidence of feeding specifically associated with grubbing for invertebrate larvae that were living within the stem tissue of twigs and branchlets (Table 3.1).

The only introduced food plant species recorded from the quadrats were cones from the exotic maritime pine *Pinus pinaster*. Since there were no specimens of *P. pinaster* growing within any of the quadrats it is assumed that the pine cones were transferred into sites. Pine cones were recorded in quadrats at Bold Park, Melaleuca Conservation Park and State Forest (north of Yanchep) and all were located adjacent to established pine plantations.

With the exception of *B. ilicifolia*, > 75% of fruiting structures handled were fed on. Proteaceous species made up 53% of plants consumed for fruiting structures. *Banksia* and *Hakea* species had the highest amounts of feeding residue. *Banksia* species were widespread across the study area with *B. attenuata* and *B. menziesii* occurring at the majority of sites (Table 1). *Hakea* species were found at fewer sites and at low densities with the exception of *H. costata* and *H. trifurcata* which were abundant in the most northern site. These *Hakeas* also coexist with the other important food plants *B. sessilis* and *Allocasuarina humilis.*

Although other species including *A. fraseriana, C. calophylla, E. marginata* and *Xylomelum occidentale* formed components of the birds' diet, the amount fed upon was either low or restricted to only a few sites. Feeding bouts on these species were generally limited to one or two feeding bouts during the year. A number of *A. fraseriana, C. calophylla* and *E. marginata* fruiting structures collected during the surveys were excluded from the results shown in Table 3.1 due to manipulation signs, which were most likely from the Red-tailed black cockatoo *Calyptorhynchus banksii naso.* Feeding traces of *X. occidentale* were pinched off along the stem and Carnaby's cockatoos were assumed to be responsible because of the similar manipulation signs observed on other plant species and also due to the thickness of the stem, which would be hard for other smaller parrot species to manipulate.

Table 3.1: Plant species and total number of fruiting structures, inflorescences or flowers and twigs selected by Carnaby's cockatoo.

Family	Species	Sites where present (%)	No. of surveys, fruiting structure recorded	Total number fruiting structures fed on	Total number fruiting structures uneaten	Total number fruiting structures grubbing signs	Total number inflorescences or flowers removed	Total number inflorescences or flowers grubbing signs	Total number twigs removed	Total number twigs signs of grubbing
Casuarinaceae	*Allocasuarina fraseriana*	57	3	35	4	0	0	0	165	1
	A. humilis	32	2	167	67	0	0	0	2	0
Fabaceae	*Jacksonia furcellata*	29	0	0	0	0	0	0	24	14
	J. sternbergiana	11	0	0	0	0	0	0	5	3
Loranthaceae	*Nuytsia floribunda*	39	0	0	0	0	203	0	41	6
Myrtaceae	*Corymbia calophylla*	7	3	25	1	0	0	0	30	0
	Eucalyptus gomphocephala	7	4	0	301	0	0	0	240	7
	E. marginata	32	1	1 177	245	0	0	0	400	1
	Eucalyptus spp.	14	0	0	0	0	0	0	81	7
	Kunzea glabrescens	11	0	0	0	0	0	0	6	6
Pinaceae	*Pinus pinaster*	0	3	7	0	0	0	0	0	0
Proteaceae	*Banksia attenuata*	96	6	1 661	427	703	1 882	709	1 417	155
	B. grandis	25	3	6	1	0	30	11	9	0
	B. ilicifolia	39	6	76	70	1	130	4	149	5
	B. menziesii	75	6	731	194	143	343	123	146	19
	B. prionotes	28	6	389	93	45	202	55	320	12
	B. sessilis	36	6	214 765	39 043	0	20 438	2	10 518	2
	Hakea costata	4	2	6 099	0	0	0	0	100	0
	H. lissocarpha	14	2	0	10	0	0	0	1	1
	H. prostrata	28	0	0	0	0	0	0	2	0
	H. trifurcata	7	2	8 508	1 769	0	0	0	205	1
	Petrophile linearis	43	0	0	0	0	0	0	3	0
	Xylomelum occidentale	14	2	164	2	0	0	0	0	0
Xanthorrhoeaceae	*Xanthorrhoea preissii*	86	1	2	0	0	0	0	0	0

Note: Not all *Eucalyptus* leaves were able to be identified to species and were grouped under *Eucalyptus* spp. Uneaten fruiting structures include fruits where all follicles may be open, closed or insect damaged.

A number of plant species were parasitised by insects whose larvae developed in or on fruiting structures, inflorescences or stems. Grubbing for invertebrates by Carnaby's cockatoos was observed in 15 plant species, of which four species (all *Banksia* spp.) had infructescences and inflorescences manipulated for insect larvae. Signs of grubbing by Carnaby's cockatoos were observed in 34% of *B. attenuata* infructescences handled, 16% of *B. menziesii* infructescences and 9% of *B. prionotes* infructescences. Inflorescences manipulated for invertebrates were recorded for *B. attenuata* (38%), *B. grandis* (37%), *B. menziesii* (36%), *B. prionotes* (27%), and to a lesser extent (< 5%) *B. ilicifolia* and *B. sessilis*. The only other plant species which had flowers manipulated was *Nuytsia floribunda*. However, *N. floribunda* flowers were manipulated for the scale bugs (order Hemiptera) attached to branches rather than nectar from flowers themselves. Twigs (where n > 13 samples) manipulated for invertebrates was highest in *Jacksonia furcellata* (58%), *B. menziesii* (13%) and *B. attenuata* (11%).

Discussion

Six of the 24 species of plants recorded during this study have not previously been identified as food items for Carnaby's cockatoos, these include *A. fraseriana* (seed and twigs for invertebrates), *A. humilis* (seed), *J. sternbergiana* (twigs for invertebrates), *Kunzea glabrescens* (twigs and invertebrates), *N. floribunda* (twigs for invertebrates) and *X. occidentale* (seed). This increases the known number of native food plants used by the Carnaby's cockatoo to 87 species. The study also added a new family of plants, the Loranthaceae in the form of *N. floribunda*. Four of the six species of the newly identified food plants have coastal sand plain distributions, while *J. sternbergiana* and *X. occidentale* have a coastal sand plain distribution as well as a distribution along the eastern margins of the Darling Scarp as far south as Kojonup (*J. sternbergiana)* and Plantagenet (*X. occidentale)* (Western Australian Herbarium 1998).

The floristic communities of the Perth Interim Biogeographic Regionalisation for Australia sub-region the Swan coastal plain are dominated by proteaceous woodlands (Western Australian Herbarium 1998). These woodlands form an important non-breeding feeding area for Carnaby's cockatoos (Saunders 1980). In this study Carnaby's cockatoos showed a strong preference for proteaceous species, in particular the *Banksia* and *Hakea* genera. Apart from proteaceous species being widely distributed across the study area (Taylor & Hopper 1988), one of the potential reasons for increased selection by Carnaby's cockatoos as food resource is due to members of the proteaceous family, in particular *Banksia*, possessing seeds rich in protein, oil and

a range of nutrients (van Staden & Comins 1976; van Staden & Brown 1977; Kuo *et al.* 1982; Pate *et al.* 1985; Lamont & Groom 1998; Stock *et al.* 2013). Proteaceous species are in general higher in protein and essential nutrients, phosphorus, total nitrogen and magnesium than non-proteaceous species (Pate *et al.* 1985). The combination of a widespread distribution and a nutritionally well balanced seed resource makes proteaceous plants highly sought after by Carnaby's cockatoos.

With 53 *Banksia* species occurring locally and dominant occurrence within plant communities on the Swan coastal plain (Western Australian Herbarium 1998), it is not surprising the large seeded *Banksia* species form the dominant dietary component for Carnaby's cockatoo in remnant vegetation areas. Favoured banksia food resource plants surrounding the Perth metropolitan and greater Perth area on the Swan coastal plain primarily include *B. attenuata*, *B. menziesii, B. prionotes, B. sessilis* and to a lesser extent *B. ilicifolia* (Table 3.1). Banksia morphology, composition, abundance and distribution vary significantly across the Swan coastal plain. *B. attenuata* and *B. menziesii* often coexist in open woodlands with well-developed mixed shrub understorey forming the most common banksia woodland type around the Perth metropolitan and northern Swan coastal plain within the research area. In contrast *B. prionotes* and *B. sessilis* commonly occur in pure stands and are restricted by soil type, however stands are often small and fragmented, surrounded by other vegetation types which are often dominated by *B. attenuata* and *B. menziesii*. *B. ilicifolia* is less common and occurs scattered across the Swan coastal plain, with higher densities found lower in the landscape where soil moisture is more readily available (Canham *et al.* 2008).

Adoption of an alternative feeding residue collection method in *B. sessilis* dominated quadrats ensured the feeding activity could be accurately recorded. Due to the small nature of *B. sessilis, H. costata and H. trifurcata* infructescences, Carnaby's cockatoos often feed directly from the plant and did not prune branches to facilitate access to the infructescences. In these quadrats residue collection trays were essential for the assessment of *B. sessilis* feeding due to the infructescences being small, and often blending into the ground due to their size and colouration. At sites where *B. sessilis* was present but was not the dominant species, fewer infructescences were collected in trays and more branches were removed by Carnaby's cockatoos with signs of feeding attached suggesting a determined feeding strategy by the cockatoos.

Although *H. costata* and *H. trifurcata* seed were consumed by Carnaby's cockatoos, these plant species were most likely fed upon as a consequence of coexisting with the prolific seeder *B. sessilis.* These proteaceous species yielded seed at the same time of

the year and this co-availability allowed the birds to feed on all available food resources in an area. Conversely, consumption of seed from eucalypts did not appear to be driven by seed availability as with the *Banksia* species. Rather eucalypts were the food resource being targeted since the feeding bouts occurred only once per year. This suggests that seed resources from eucalypts are only available for a short period of time unlike *Banksia* species which appear to be available for much longer periods of the year. Feeding behaviour of the birds appears to be a consequence of availability as well as energetic reward, and further research is discussed in later chapters.

It is interesting to note that 68% of plant species fed on by Carnaby's cockatoo, in this study, were for insect larvae. *Banksia* species appear to carry the highest insect larvae load as seen from the cockatoo extraction figures for infructescences, inflorescences and twigs. In many cases it was hard to distinguish whether the presence of invertebrates was the primary driver for consumption or the reward was seed or nectar. Increased grubbing of *Banksia* species may be directly proportional to infructescence or inflorescence size, as suggested by Scott and Black (1981). *B. attenuata* recorded the highest grubbing activity for both infructescences and inflorescences. Although *B. attenuata* has the third largest inflorescence for the species recorded in this study, its increased presence in banksia woodlands, and high numbers of inflorescences compared to *B. grandis* and *X. preissii* which have larger inflorescences, increased the chance of insect activity.

This study has increased the documented numbers of plant species that Carnaby's cockatoo feed on, both directly (fruiting structures and inflorescence or flowers) and indirectly (insect larvae). In particular, this study highlighted the strong relationship between Carnaby's cockatoos and Proteaceous species, especially *Banksia* and *Hakea* species, as a food resource in banksia woodlands. Banksia plants provide a wide variety of food types which include seed, nectar and invertebrates. Further research into the spatial and temporal availability of the main dietary components such as banksia infructescences, would help further elucidate the importance of each species and identify if certain species were fed upon opportunistically or were the drivers of Carnaby's cockatoo feeding events. Also an investigation into the energetics of key seed food resources in relation to availability, abundance and seed weight would help identify why, or if, certain species are favoured more than others (See Chapters 5 and 6).

Chapter 4: Banksia infructescence availability on the Swan coastal plain

Introduction

Many factors affect the distribution and abundance of cockatoos in Western Australia. The availability of nesting hollows (Saunders *et al.* 1985; Rowley & Chapman 1991; Mawson and Long 1994) and food resources (Saunders 1980; Berry and Owen 2010) are likely to have an important influence on both the abundance and distribution of the birds. Extensive land clearing for agriculture and urban development, the introduction of plant diseases and altered fire regimes have resulted in the destruction of habitat for Carnaby's cockatoos (Saunders 1979b, 1980, 1986, 1990; Saunders and Ingram 1987, 1995, 1998; Saunders *et al*. 1985; Mawson and Johnstone 1997). As a consequence, Carnaby's cockatoo is now listed as threatened under State and Commonwealth legislation (Wildlife Conservation Act 1950; Environment Protection and Biodiversity Conservation Act 1999). The reduction in the availability of quality foraging resources is suggested to be a key factor contributing to population decline and range contraction for the species (Saunders 1980, 1990; Berry & Owen 2010: Garnett *et. al* 2011). In particular, a decline in food resource availability in non-breeding areas is believed to be contributing to a reduction in numbers (Berry & Owen 2010). In this study the seasonal and annual availability of banksia infructescences, an important food resource for Carnaby's cockatoo (Saunders 1980; Shah 2006; Valentine & Stock, 2008; Chapter 3), was examined to investigate the variability in valued food resources across the Swan coastal plain.

Food availability studies contribute to our understanding of population and community level consequences when considering limitations of food resources (Hutto 1990). The relationship between Carnaby's cockatoos and *Banksia* species as importance food sources is well documented (Saunders 1980; Shah 2006; Valentine & Stock, 2008; Chapter 3). *Banksia* food resource plants for Carnaby's cockatoos on the Swan coastal plain include *B. attenuata, B. menziesii, B. grandis, B. ilicifolia, B. prionotes* and *B. sessilis* (Saunders 1980; Scott & Black 1981; Shah 2006; Valentine & Stock, 2008; Chapter 3). However, past research has focused (e.g. Perry 1948; Saunders 1980; Scott & Black 1981; Shah 2006) on the presence/absence of feeding, with little information on the seasonal availability and annual production of food resources. In addition the influence of soil type and fire on banksia infructescence production has only been investigated by Valentine and Stock (2008) as part of the Gnangara

Sustainability Study which was restricted to the Gnangara area (Perth northern metropolitan area) and only focused on *B. attenuata* and *B. menziesii.* Despite establishing potential food availability estimates, the study identified that more accurate estimates of standing crop of banksia seeds needed to be developed and the impact of disturbance factors such as *P. cinnamomi* (dieback) addressed.

The distribution, abundance and availability of food resources are closely linked to environmental factors such as rainfall and temperature (Salisbury 1992; Reed *et al.* 1994; Schwartz 1994; Studds & Marra 2011). Similarly, disturbance is an integral part of every ecosystem, shaping the spatial and temporal availability of resources and their heterogeneity (Walker 2011). Fire plays an important role in shaping the structure and composition of banksia woodlands (Lamont & Baker 1988; Enright & Lamont 1989; Witkowski *et al.* 1991; Lamont *et al.* 1999; Valentine & Stock 2008) with banksia assemblage and standing seed crop availability determined by the frequency and intensity of fire (Lamont *et al.* 1999). Disease such as the soil dwelling pathogen *P. cinnamomi* can have a considerable impact on the production of seed by the host plant. Shearer and Hill (1989) reported *Phytophthora* as the most frequent cause of plant deaths in susceptible species. Banksia plants are highly susceptible to *P. cinnamomi* which causes irreversible damage by altering the diversity, standing seed crop size and ecological processes (Hill *et al.* 1994; Shearer & Hill 1989; Keighery *et al.* 1994; Shearer & Dillon 1996a; Shearer & Dillon 1996b; Shearer 2007). Understanding the response of plants to external factors can help to determine the amount of food available of key food species. In turn, this can be used to identify important feeding habitat for Carnaby's cockatoo and help manage and conserve the species.

The objective of this study was to better understand the influence of external factors on the standing crop of banksia infructescences in proteaceous woodlands on the Swan coastal plain. The numbers of drying infructescences of *B. attenuata, B. menziesii, B. grandis, B. ilicifolia, B. prionotes* and *B. sessilis* were investigated to determine the variability in seasonal and annual numbers produced. In addition, soil type, disease and time since last fire were examined to determine the influence of these factors on infructescence numbers. Allometric relationships between plant morphology and number of infructescences were developed to identify characteristics which affect banksia infructescence standing crop availability.

Study Site

This study was undertaken across the Swan coastal plain from south of Guilderton (31° 20’ S) to the southern boundary of Waroona Shire (32° 55′ S). The area is bounded by the Indian Ocean to the west and Darling Scarp (116° 02’ E) to the east. Situated on the western edge of Australia, the study area covers an area of 5 075 km^2 (approximately 170 km in length and 25 km wide). The region has a mediterranean type climate with nutrient poor soils and an annual rainfall of 600-1 000 mm (Beard 1984).

The Swan coastal plain vegetation is characterised by Proteaceous woodlands, eucalyptus forest, and paperbark *Melaleuca* spp. dominated wetlands (Beard 1980; Heddle *et al.* 1980; Gibson *et al.* 1994; Mattiske & Havel 1998). Banksia woodlands form a dominant vegetation component on the Swan coastal plain, (Beard 1980; Heddle *et al.* 1980; Gibson *et al.* 1994; Mattiske & Havel 1998) exhibiting strong associations with three land types - Pinjarra Plain, Bassendean Dunes, Spearwood Dunes - and to a lesser extent with the Quindalup Dunes (McArthur and Bettenay 1960).

Methods

Study sites were selected across the Swan coastal plain in banksia dominated woodlands. Coastal, wetland and transition vegetation zones were excluded from site selection. Eighty-four 20 m x 20 m quadrats were established across 21 bushland sites. These sites comprised a range of landform types, time since last fire, vegetation health conditions and banksia communities. A minimum of three representative quadrats were established within each of the 21 sites for each selected landform type, time since last fire, vegetation health condition and banksia community. Quadrats were marked by inserting fence droppers in each corner.

The number of drying banksia infructescences, which represented the standing crop containing seeds, and Carnaby’s cockatoo banksia feeding residues were recorded over a 12 month period, December 2010 to December 2011. Drying infructescences were classified as infructescences that were held in the canopy with all follicles closed and fully developed. The numbers of drying infructescence were recorded for each quadrat at the end of the survey period using Bell and Stephens (1984) banksia reproductive phenophases. Feeding residue surveys identified and recorded the number of eaten and uneaten infructescences that appeared to have been manipulated

by Carnaby's cockatoos for each species. The numbers of drying infructescences and Carnaby's cockatoo manipulated infructescences were combined to establish the amount of banksia food available. For *B. sessilis* stands an alternative method was used due to the high density of stems and differences in infructescence morphology from other species of *Banksia*. Three 2 m x 2 m nested quadrats were randomly established within the larger 20 m x 20 m quadrat. Two 0.5 m x 0.5 m residue trays were placed in the nested quadrats to collect discarded infructescences. Two residue trays were also placed in quadrats where density of *B. sessilis* stems were low and the results scaled up by a factor proportional to the total canopy area that *B. sessilis* contributed for that site.

The number of banksia infructescences available (infructescence drying in the canopy and those manipulated by Carnaby's cockatoo) for each species was compared between landform type (soil), time since last fire and in the presence and absence of *P. cinnamomi* (health condition). Plants with no reproductive structures present (i.e. plants that were either juveniles, immature, stunted or resprouting from base) were not included in infructescence standing crop counts. Non-reproductive plants were excluded as future infructescence contribution is unknown and inclusion would reduce average number of infructescences available per reproductive plant. Allometric relationships between plant morphology characteristics and number of infructescences were established to identify primary factors which might affect the size of infructescence standing crop availability. Statistical software package SPSS v18 was used for all statistical analyses.

Soil

Soil types were determined by examining existing government spatial data sets for each of the study sites. Sites were selected across the main landform systems within the study area, Quindalup Dunes, Spearwood Dunes and Bassendean Dunes. Banksia woodlands on the Quindalup dune system were limited (only one site investigated as part of this study) and were therefore excluded from the analysis for soil effects. Data were analysed using independent-sample t-tests of log transformed data with a factor of soil type and dependent variable of the number of banksia infructescences.

Disease

Sites that have been, or are currently infected with *P. cinnamomi* were selected for analysis of food resource availability in diseased areas. Government spatial data sets

were accessed in addition to an on-ground assessment to evaluate disease presence. On-ground assessments were carried out using the Department of Environment and Conservation (DEC WA) dieback interpretation techniques (CALM 2001). Assessment involved identifying the presence of plant disease in indicator species, such as loss of foliage, yellowing in leaves, thinning of understorey vegetation and distribution and spread of dead trees. Two soil samples were also collected from each quadrat to identify any current presence of disease. Soil sampling was undertaken randomly unless areas within the quadrat displayed signs of dying or very recently-killed indicator plant species. Soil and root material were collected as per DEC guidelines. DEC WA disease risk management hygiene standards were adhered to during this study (CALM 2001). The mean numbers of *Banksia* infructescences in the presence and absence of *P. cinnamomi* were only tested on Bassendean soils due to the disease's strong association with this soil type (Shearer and Dillon 1996). The influence of *P. cinnamomi* was tested between sampling pairs (disease site vs. non disease site in similar locality). Data were not normally distributed and therefore analysed using the Kruskal-Wallis test with a factor of disease presence and dependent variable of number of *Banksia* infructescences available.

Fire

Government spatial data sets were utilised to determine the time since last fire at all study areas. Ground-truthing was required for some quadrats whereby maps were used in conjunction with general observations (e.g. fire scars and presence of fire colonising species such as *Acacia pulchella*) of the site. Additionally stand age was analysed via node counts, whereby banksia plant growth nodes (number of junctions between growth increments) were counted to assist with time since last fire (Wills 2003). For non-DEC managed lands property owners and managers were consulted to assist with fire history information. Prior to analysis, data were screened for normality and equality of variance. Five fire categories were analysed for *B. attenuata* and *B. menziesii*, ≤ 5, 6-10, 11-15, 16-20 and ≥ 21 years since last fire. Only three fire categories were analysed for *B. sessilis* due to the variability in stems per quadrat and small quadrat sample size in relation to time since last fire. A one-way analysis of variance test was conducted on square root transformed data for the number of *B. attenuata* infructescences and a post hoc Tukey-b (for unequal sample sizes) analysis undertaken to determine which means significantly ($P < 0.05$) differed. Kruskal-Wallis tests were conducted for the number of *B. menziesii* and *B. sessilis* infructescences in relation to time since last fire due to data not being normally distributed.

Plant allometry

All mature banksia plants within each quadrat were measured to determine the allometric relationships between plant morphological characteristics and the number of infructescences to identify factors which might predict the size of the infructescence standing crop. Trunk diameter was measured at 0.5 m height above ground level using a tape measure for all species except *B. sessilis* which was measured at 0.25 m height due to the morphological characteristics of the species (short trunk to first branching). Where there was more than one stem, each stem was measured and a single girth calculated with the same total cross-sectional area, assuming cylindrical stems (total girth = square root of sum of squares of separate girths). A range pole was used to measure upper and lower plant foliage height, as well as canopy width. Where the tree was taller than the range pole an estimate was made using replicated increments of measure using the range pole as a known height. The height (H) and the widest (W_1) and perpendicular (W_2) widths of each mature tree were used to calculate canopy area ($\pi * W_1/2 * W_2/2$) and canopy volume ($4/3\ \pi * W_1/2 * W_2/2 * H/2$) for an ellipse/ellipsoid canopy (Witkowski *et al.* 1991). Relationships between variables were first analysed using bivariate correlation and then further investigated with multiple linear regression to establish which independent factor(s) best predicted infructescence numbers. Analyses were conducted on all quadrat data.

Banksia infructescence phenology

Infructescence phenology was recorded over a 12 month period to determine seasonal variation in number of infructescences. Infructescence total standing crop was recorded bi-monthly which included counting the number of drying (all follicles closed), partially open (half follicles open) and open (all follicles open) infructescences. The number of drying infructescences was compared to the total number of infructescences in the standing canopy to determine if external factors, such as foraging, were observable. Each of the main food resource species was assessed by counting the number of infructescences on three randomly selected mature trees for each of the species present within each of the quadrats. Individual plants of each *Banksia* species present in a given quadrat were marked with numbered metal tags. Where there were fewer than three individuals in the quadrat, the nearest plant(s) outside the quadrat within a 50 m radius was examined. Newest structures were determined by growth nodes, whereby infructescences counted were no more than two growth nodes from the distal end of the branch.

Results

Influence of soil on infructescence numbers

The mean number of drying and Carnaby's cockatoo manipulated infructescences for *B. attenuata, B. menziesii* and *B. grandis* on Spearwood and Bassendean soil types were similar (Table 4.1). Independent-sample t-tests conducted on log-transformed data for *B. attenuata* and *B. menziesii* showed no statistically significant differences ($P > 0.05$) between the number of infructescences between soil types (*B. attenuata* $t_{[22]} = 0.76$, $P = 0.940$, n = 24; *B. menziesii* $t_{[18]} = -1.568$, $P = 0.134$, n = 20). Only Bassendean and Spearwood soil types were investigated due to the restricted number of banksia woodlands on Quindalup soils. *B. sessilis* and *B. prionotes* were only investigated on Spearwood soils since they do not normally occur on the Bassendean soil type while *B. ilicifolia* plants were only recorded on Bassendean soils. *B. grandis* was not statistically analysed since it was only found at a small number of sites and at low plant densities.

Table 4.1: Annual number of banksia infructescences and number of stems on Bassendean and Spearwood soils.

Species	Soil Type	*n* (no. sites)	Mean no. stems ± SE (ha)	Mean no. drying infructescences ± SE (ha)
B. attenuata	Bassendean	10	155.0 ± 23.8	343.3 ± 70.4
	Spearwood	14	117.5 ± 29.8	345.2 ± 103.3
B. grandis	Bassendean	2	5.8 ± 2.7	14.2 ± 5.6
	Spearwood	2	14.2 ± 11.1	4.2 ± 1.4
B. ilicifolia	Bassendean	8	12.5 ± 2.3	555.8 ± 471.7
B. menziesii	Bassendean	9	110.8 ± 23.4	193.3 ± 52.7
	Spearwood	11	64.2 ± 10.3	135.8 ± 48.1
B. prionotes	Spearwood	3	2 077.5 ± 12 470.4	2 552.8 ± 1 552.7
B. sessilis	Spearwood	8	4 054.2 ± 3 944.8	351 659.4 ± 239 842.2

Influence of P. cinnamomi on infructescence numbers

The number of infructescences differed significantly ($P < 0.05$) for *B. attenuata* ($k_{[1]} = 5.17$, $P = 0.023$, n = 14) and *B. menziesii* ($k_{[1]} = 4.30$, $P = 0.038$, n = 9) in relation to disease presence (Table 4.2). The mean number of stems per ha^{-1} for *B. attenuata* was

5.3 times greater and for *B. menziesii* 9.6 times greater in non *P. cinnamomi* sites compared with *P. cinnamomi* infected sites. Owing to the small number of *B. ilicifolia* plants analysed statistical significance was not tested.

Table 4.2: Annual number of banksia infructescences and number of stems in sites with and without *P. cinnamomi*.

Species	*P. cinnamomi* (PC)	*n* (no. quadrats)	Mean no. stems ± SE (ha)	Mean no. drying infructescences ± SE (ha)
B. attenuata	PC	5	65.0 ± 18.8	360.0 ± 87.5*
	Non PC	9	342.5 ± 54.3	865.0 ± 161.8*
B. ilicifolia	PC	2	137.5 ± 87.5	2 850.0 ± 185.5
	Non PC	3	82.5 ± 46.5	2 325.0 ± 74.8
B. menziesii	PC	3	32.5 ± 8.3	167.5 ± 16.8*
	Non PC	6	312.5 ± 66.8	1 270.0 ± 283.5*

** Significant difference*

Influence of time since last fire on infructescence numbers

The mean number of drying and Carnaby's cockatoo manipulated infructescences for *B. attenuata, B. menziesii* and *B. sessilis* in relation to time since last fire differed significantly ($P < 0.05$) (*B. attenuata* $F_{[4,64]} = 4.86$, $P = 0.002$, n = 69*; B. menziesii* $k_{[4]} = 15.26$, $P = 0.004$, n = 46; *B. sessilis* $k_{[2]} = 9.08$, $P = 0.003$, n = 17) (Table 4.3). The post hoc test (Tukey-b) for *B. attenuata* showed that post-fire stands < 10 years displayed similar means, intermediate post-fire interval stands (6-10 and 11-15 years) were not significantly ($P < 0.05$) different from each other and sites where fire last occurred > 16 years ago were also not significantly different. Mean rank scores for *B. menziesii* showed similar results to that of *B. attenuata* whereby recent post-fire stands (≤ 5 and 6-10 years) were not significantly different. *B*. *menziesii* sites > 16 years post-fire were similar to recent fire stands and intermediate post-fire interval stands (11-15 years) were more similar to older post-fire stands than younger post-fire stands. *B. menziesii* showed the highest number of infructescences in stands 11-15 years post-fire, whereas stands where fire occurrence was > 16 years shared a similar value to stands < 10 years since last fire. Peak infructescence production in *B. sessilis* occurred between 6-15 years since last fire. Mean rank scores suggest a greater difference between stands ≤ 5 years since last fire compared to stands > 5 years since last fire. *B. prionotes* was not tested because of the limited number of sites at which this species

was found (Table 4.1). *B. ilicifolia* was not tested due to the absence of quadrats for time since last fire categories ≤ 5, 6-10 and 16-20 years post-fire.

Table 4.3: Mean number of banksia infructescences and stems relative to time since last fire (TSLF). Results from Post hoc Tukey–b tests are shown for *B. attenuata (a, b, c)*, whereby categories with the same letter had significantly ($P < 0.05$) similar means.

Species	TSLF (yrs.)	*n* quadrats	Mean no. stems ± SE (ha)	Mean no. infructescences ± SE (ha)
B. attenuata	≤ 5	8	275.0 ± 52.0	287.5 ± 111.5 [a]
	6-10	9	652.5 ± 184.0	577.5 ± 145.3 [ab]
	11-15	12	375.0 ± 45.3	1 125.0 ± 226.0 [b]
	16-20	8	355.0 ± 43.0	1 962.5 ± 579.3 [c]
	≥ 21	32	667.5 ± 113.8	1 367.5 ± 256.0 [c]
B. menziesii	≤ 5	5	240.0 ± 105.8	185.0 ± 103.3
	6-10	3	467.5 ± 129.3	357.5 ± 209.3
	11-15	9	365.0 ± 77.0	1 310.0 ± 205.5
	16-20	8	242.5 ± 73.5	725.0 ± 311.8
	> 21	21	432.5 ± 88.3	452.5 ± 78.8
B. sessilis	≤ 5	5	32 770.0 ± 18 692.8	325.0 ± 300.5
	6-15	5	19 095.0 ± 8 645.3	1 315 052.5 ± 454 533.3
	≥ 16	7	240.0 ± 72.3	266 870.0 ± 161 677.0

Plant allometry

The allometric relationships between plant morphological characteristics and the number of infructescences were analysed separately for each *Banksia* species (Table 4.4). The number of infructescences for *B. attenuata* showed significant ($P < 0.05$) correlations with girth, canopy area, canopy volume and plant age, while *B. menziesii* showed significant correlations with plant foliage height, girth, canopy area and canopy volume. *B. sessilis* showed a strong correlation with all morphological characteristics.

Pearson's correlation coefficient testing for *B. ilicifolia* and *B. prionotes* did not reveal any allometric relationships. Only a small number of *B. ilicifolia* plants were measured, which most likely contributed to no signification relationships. For *B. prionotes* the most likely reason was due to the low number of sites sampled. *B. grandis* was not tested as there were only 10 reproductive plants.

Table 4.4: Pearson's correlation coefficient tests of plant morphological characteristics in relation to number of infructescences for each *Banksia* species. Pearson's correlation (*r*) shows the magnitude and direction of the association between number of infructescences and morphological characteristic. Significance level $P < 0.05$ (bold).

Species		*n* quadrats	Average number of reproductive stems (ha^{-1})	Foliage height (m)	Height (m)	Girth (cm)	Canopy area (m^2)	Canopy volume (m^3)	Plant age (yrs)	No. of reproductive stems per quadrat
B. attenuata	*r*	75	360	0.097	0.097	0.238	0.364	0.373	0.373	0.025
	P			0.408	0.410	**0.040**	**0.001**	**0.001**	**0.001**	0.830
B. ilicifolia	*r*	13	58	0.182	0.339	0.466	0.251	0.097	0.237	0.324
	P			0.552	0.257	0.109	0.407	0.753	0.435	0.280
B. menziesii	*r*	49	272	0.317	0.201	0.317	0.397	0.479	0.206	0.187
	P			**0.026**	0.167	**0.027**	**0.005**	**0.001**	0.155	0.198
B. prionotes	*r*	7	2077	0.271	0.150	0.206	0.472	0.546	0.224	0.200
	P			0.557	0.748	0.658	0.285	0.205	0.629	0.667
B. sessilis	*r*	14	6950	0.920	0.857	0.730	0.949	0.819	0.935	0.819
	P			**0.000**	**0.000**	**0.003**	**0.000**	**0.000**	**0.000**	**0.000**

Results from the linear regression analysis are shown in Table 4.5. For *B. attenuata*, canopy volume, canopy area and girth emerged as the best individual predictive models for explaining the variability of the number of infructescences. Multiple linear regression of all *B. attenuata* plant morphological variables accounted for 29% of the variability in the number of infructescences. Canopy volume, canopy area, girth and foliage height were the best individual predictive models for determining the number of infructescences for *B. menziesii*. The combination of all *B menziesii* plant morphological characteristics explained 44% of the variability in the number of infructescences. All the models tested for *B. sessilis* revealed significant ($P < 0.05$) relationships with correlation coefficients > 53%. Canopy area was the best individual predictive factor for *B. sessilis,* accounting for around 90% of the variation. Multiple linear regression analysis combining all *B. sessilis* plant morphological variables revealed a correlation coefficient of 92%.

Table 4.5: Regression coefficients of the number of mature and Carnaby's cockatoo manipulated infructescences in relation to independent variables of plant morphological characteristics per quadrat (400m^2). Significance level $P < 0.05$.

	Variables	Coeff.	SE	*F*	d.f.	*P*	r^2
B. attenuata	Constant	37.04	8.50	0.69	1.73	0.41	0.01
	Height	0.08	0.10				
	Constant	36.67	8.82	0.69	1.73	0.41	0.01
	Foliage height	0.15	0.18				
	Constant	25.57	9.65	4.38	1.73	0.04	0.06
	Girth	2.46	1.18				
	Constant	20.41	8.32	11.17	1.73	0.00	0.13
	Canopy area	0.18	0.05				
	Constant	23.27	7.53	11.78	1.73	0.00	0.14
	Canopy volume	0.07	0.02				
	Constant	41.08	8.42	0.05	1.73	0.83	0.00
	No. of reproductive stems	0.10	0.44				
	Constant	37.96	8.64	0.45	1.73	0.51	0.01
	Age	0.01	0.02				
	Constant	6.05	10.29	4.69	6.68	0.00	0.29
	Height	-1.57	0.59				
	Foliage height	0.46	0.54				
	Girth	12.39	5.41				
	Canopy area	0.17	0.15				
	No. of reproductive stems	-1.02	1.93				
	Age	0.11	0.08				
B. menziesii	Constant	18.22	5.12	1.97	1.47	0.17	0.04
	Height	0.13	0.91				
	Constant	14.33	5.19	5.26	1.47	0.03	0.10
	Foliage height	0.40	0.18				
	Constant	13.80	5.38	5.25	1.47	0.03	0.10
	Girth	2.38	1.04				
	Constant	11.28	5.21	8.80	1.47	0.01	0.16
	Canopy area	0.20	0.07				
	Constant	9.36	4.85	13.96	1.47	0.00	0.23
	Canopy volume	0.12	0.03				
	Constant	18.50	5.18	1.71	1.47	0.20	0.04
	No. of reproductive stems	5.17	3.96				
	Constant	18.28	5.00	2.09	1.47	0.16	0.04
	Age	0.24	0.02				
	Constant	6.95	4.82	5.58	6.42	0.00	0.44
	Height	-1.09	0.34				
	Foliage height	1.37	0.48				
	Girth	9.68	5.39				
	Canopy area	0.18	0.15				
	No. of reproductive stems	-4.25	1.97				
	Age	0.10	0.73				
B. sessilis	Constant	9 176.93	5 489.32	33.29	1.12	0.00	0.74
	Height	51.20	8.88				
	Constant	7 922.13	4 191.36	66.03	1.12	0.00	0.85
	Foliage height	86.60	10.66				
	Constant	12 816.58	7 117.30	13.67	1.12	0.00	0.53
	Girth	479.27	129.61				
	Constant	1 943.11	3 634.86	109.58	1.12	0.00	0.90
	Canopy area	280.86	26.83				
	Constant	1 389.14	7 090.31	24.42	1.12	0.00	0.67
	Canopy volume	350.43	70.91				
	Constant	10 618.46	6 047.13	24.44	1.12	0.00	0.67
	No. of reproductive stems	48.54	9.82				
	Constant	9 614.12	5 869.14	27.56	1.12	0.00	0.70
	Age	6.41	1.22				
	Constant	158.28	4 547.68	26.76	4.9	0.00	0.92
	Foliage height	15.62	40.17				
	Girth	608.28	474.77				
	Canopy area	390.76	153.71				
	Age	-10.67	7.47				

Banksia infructescence phenology

Drying infructescences were present all year for each species (Figure 4.1) except *B. grandis*, for which infructescences were only recorded during three survey periods (December, February and October). Production of new *B. grandis* infructescences peaked in December and then dropped by 66% by February. *B. menziesii* shared a similar pattern to *B. grandis* with peak infructescence numbers found in December. Over 50% of *B. menziesii* infructescences present in December were from the 2010 season and by February 2011 new infructescences only accounted for 14% of the total present. Like *B. menziesii* and *B. grandis*, *B. ilicifolia* had the greatest number of infructescences in December (31% of the total), however the decline of new infructescences was more gradual with lowest availability shown in August (Figure 4.1) Conversely, *B. attenuata* had the greatest number of new infructescences in August (23% of the total), with lowest number recorded in February (8% of the total). *B. prionotes* new infructescence production began to increase in June, peaking in December (36% of the total). Similarly, *B. sessilis* had the greatest number of new infructescences in December (25% of the total), gradually falling away throughout the year with October recording < 1% of the total (Figure 4.1).

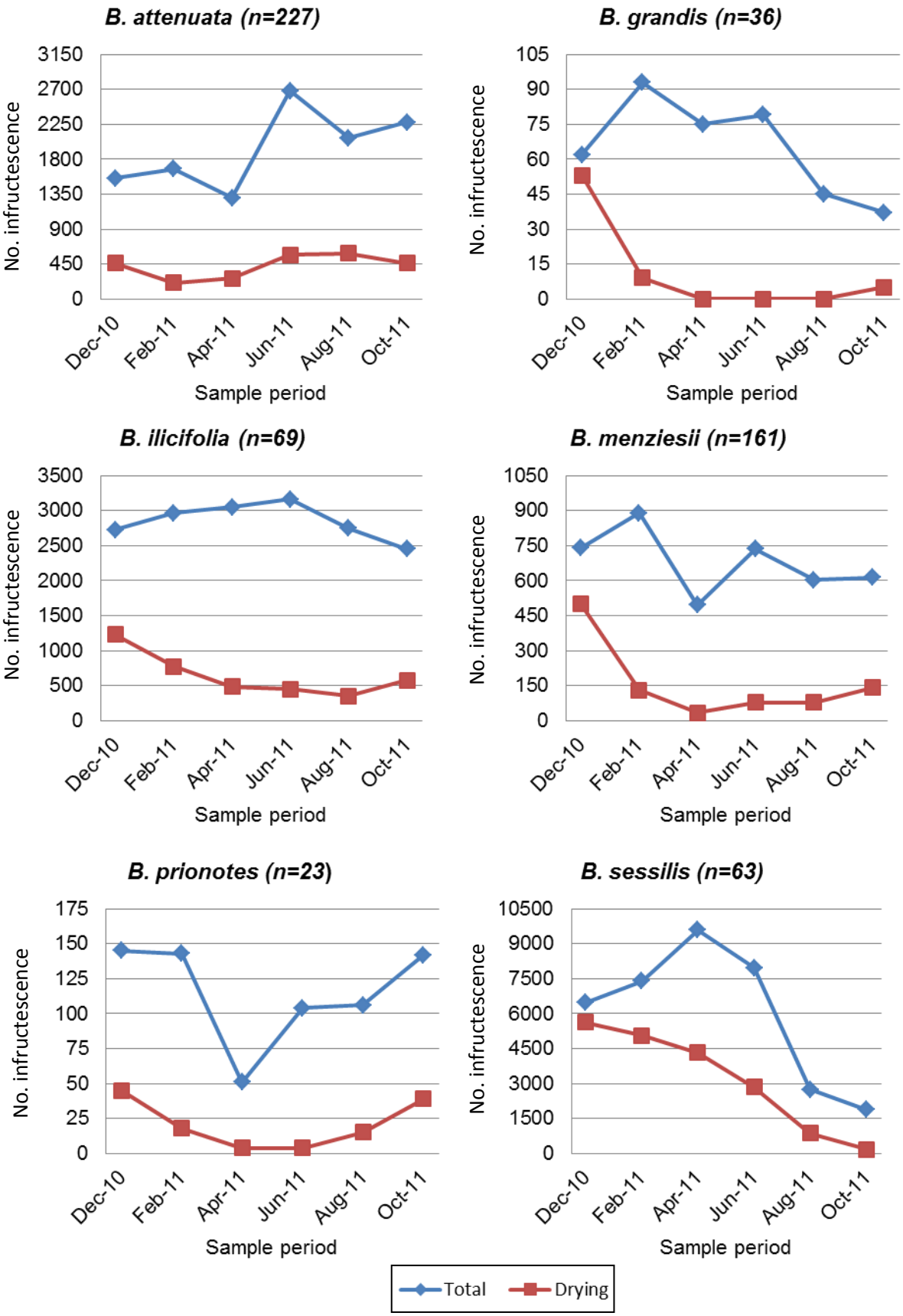


Figure 4.1: Total number of infructescences and number of current season (drying) infructescence recorded from December 2010 to October 2011 over all quadrats (3.36 ha).

Discussion

B. attenuata and *B. menziesii* are the most common banksia woodland plants on the Swan coastal plain (Taylor & Hopper, 1988) and often coexist in open woodlands with well-developed mixed shrub understorey. In contrast *B. prionotes* and *B. sessilis* commonly occur in pure stands with a high density of stems. *B. grandis* and *B. ilicifolia* are less common and occur scattered across the Swan coastal plain, with *B. ilicifolia* typically found lower in the landscape where soil moisture is more readily available (Canham *et al.* 2008). The influence of fire and disease on banksia woodlands is also highly variable with these factors shaping the structure, morphology, abundance and distribution of *Banksia* species. Understanding this variability is necessary if land managers wish to assess banksia woodlands as potential food resources for the threatened Carnaby's cockatoo.

It was not unexpected that this study showed that infructescence numbers do not differ significantly ($P < 0.05$) between Bassendean and Spearwood soil types. In this study banksia woodlands were predominantly studied on the Spearwood and Bassendean Dune Systems, with only one site located on the Quindalup Dune System due to the lack of banksia woodland sites on this soil type. The Spearwood and Bassendean Dune Systems are both characterised by Pleistocene aeolian deposited sands, however the Bassendean Dune System is older consisting of undulating hills of heavily leached sands. Despite this difference they are both dominated by nutrient-poor soils and exposed to similar climatic conditions (McArthur and Bettenay 1960).

This study demonstrates the influence of dieback disease with both *B. attenuata* and *B. menziesii* recording significant ($P < 0.05$) differences between the mean numbers of infructescences available in the presence and absence of the disease. The numbers of reproductive plants and infructescences are reduced by disease presence. *P. cinnamomi,* like banksia woodlands, has a strong association with geomorphic elements with 50% of *P. cinnamomi* centres on the Swan coastal plain associated with the Bassendean Dune System (Shearer & Dillon 1996a). As a consequence of this relationship, *P. cinnamomi* was only investigated on Bassendean soils. *P. cinnamomi* is a major threat to the ecology of susceptible plant communities which include banksia woodlands (Shearer 1990) and has been reported as the most frequent cause of plant death (Shearer & Hill, 1989). The impact of *P. cinnamomi* on plant species numbers, and in particular banksias, on the Swan Coastal Plain is well documented (Shearer & Hill 1989; Shearer & Dillion 1996a, 1996b). However past research has focused on the

decline of plant species in the presence of *P. cinnamomi*, rather than the change in quantity of food resources. Few disease centres are found on the soils of the Spearwood and Quindalup Dune Systems (Shearer and Dillon 1996a) as a consequence, the effect of the *P. cinnamomi* on *B. prionotes* and *B. sessilis* stands was not investigated as these *Banksia* species are strongly associated with the Spearwood soils. It is therefore reasonable to suggest that *P. cinnamomi* has a greater impact on banksia woodlands located on Bassendean soils. However, susceptibility as determined by laboratory trials is not a true reflection of likely impact in the wild (Shearer and Dillon 1996a; Shearer 2007). Despite the presence of *P. cinnamomi* in many banksia woodlands, the disease is often patchy in its expression with islands of healthy vegetation persisting. Disease resistance and/or disease fronts can skew results. Species that are susceptible to *P. cinnamomi* but have individuals which are more tolerant than others, or are not yet affected by the disease, can show higher than expected infructescence yields due to reduced competition for resources (e.g. light, water, nutrients). Knowledge of disease occurrence, likely spread and the impact on the numbers of infructescences can be used to assist with conservation management of feeding habitat for Carnaby's cockatoos.

Knowledge of infructescence maturation is also important to understand when food resource availability for Carnaby's cockatoo is at its peak since the birds often consume infructescences as they are maturing. *B. sessilis* peak infructescence production occurred earlier in the year than for *B. attenuata* and *B. menziesii. B. sessilis* is a disturbance opportunist (Rockel *et al.* 1982), colonising quickly after fire (Lamont *et al.* 1991, 1998). Once maturity is reached there is an infructescence production explosion, then standing crop availability starts to drop away. To ensure survival, seed release and disturbance need to occur at similar times. Consequently, *B. sessilis* peak drying infructescence availability coincides with summer which is the most likely season associated with fire. Since *B. sessilis* seed is not retained (weak to no serotiny) (Hanley & Lamont 2001) and short-lived (Lamont *et al*. 1998) infructescence production occurs for a longer period of time with seed maturation occurring between December and June then rapidly falling away. This ensures viable seed is available to coincide with a disturbance such as fire. However, if fire is too frequent, available seed will be low, reducing the level of recruitment. In comparison, *B. attenuata* and *B. menziesii* have a delayed infructescence production in the presence of fire. The number of *B. attenuata* infructescences gradually increases with the peak occurring after 16-20 years since last fire with an average of 1 665 infructescences ha^{-1} compared to 663 infructescences ha^{-1} for stands 11-15 years of age. A slight drop in

number of infructescences occurs in stands > 20 years post-fire but it is not significant ($P < 0.05$). However, given stands > 20 years since last fire had 32 quadrats sampled compared to eight quadrats for 16-20 year stands, this may not be a true indicator of infructescence decline as plant age increases and further investigation is required. *B. menziesii* had the greatest number of infructescences between 11-15 years post-fire and then plateaued. Less tolerant to fire than *B. attenuata* (Lamont & van Leeuwen 1988), *B. menziesii* peak infructescence availability occurred earlier in the year than for *B. attenuata*.

Banksia species can be broadly categorised into two groups, resprouters and obligate reseeders. Obligate reseeders rely on seed to reproduce (Gill & Bradstock 1992), whereas resprouters can reproduce by seed and concealed epicormic buds which shoot after disturbances such as fire or drought (Keeley 1986). As a consequence, it is this reproductive difference which allows certain *Banksia* species to persist after fire and why *B. sessilis* peak infructescence production occurs earlier after fire than for *B. attenuata* and *B. menziesii.* Obligate seeders like *B. sessilis* and *B. prionotes* (Taylor & Hopper 1988; Lamont *et al.* 2007), rely on germination of seed for survival after fire (Gill & Bradstock 1992). To ensure replacement a minimum fire-free period is required after germination for sufficient seed bank storage (Lamont & Markey, 1995). Reseeders take three to five years to first fruiting (Witkowski *et al.* 1991), growing faster than resprouters (Pate *et al.* 1990). Resprouters which include *B. attenuata, B. grandis, B. ilicifolia* and *B. menziesii* have the added advantage compared to obligate seeders of being able to regenerate from epicormic buds, provided a threshold size has been reached, whilst also being able to germinate from seed (Keeley 1986; Lamont & Markey 1995). *B. attenuata* can resprout after fire once they have reached five years old, whereas other species become fire tolerant much later (Lamont & van Leeuwen 1988, Lamont *et al.* 2007). Mature plants that resprout after fire may resume flowering one to three years after fire (Lamont & van Leeuwen 1988; Lamont & Markey 1995, Lamont *et al.* 2007), however *B. menziesii* is less tolerant of fire than *B. attenuata* (Lamont & van Leeuwen 1988), taking longer to recover post-fire. Seedlings of resprouting species can have long maturation periods (> 17 years), with *B. grandis* requiring > 18 years to reach first fruiting (Abbott 1985) and *B. tricuspis* requiring > 17 years fire free period to set seed (George 1981, van Leeuwen & Lamont 1986; Lamont & van Leeuwen 1988). Therefore, the ability of mature plants to be able to resprout following fire and the ability to produce infructescences in a relatively short period of time post-fire provides cockatoos with food resources sooner after fire than is the case for reseeding *Banksia* species.

Fire is a dynamic and multifaceted disturbance factor. Not only is time since last fire relevant to distribution, abundance and resource availability of banksia communities but fire frequency and intensity are also important factors (Cowling & Lamont 1987; Cowling *et al.* 1987; Lamont & van Leeuwen 1988; Enright & Lamont 1989). It is important to note that frequency and intensity were not investigated during this study and further research would prove useful in determining the response of different *Banksia* species.

Plant allometry studies seek to uncover relationships between easily measured variables (such as height, stem diameter, and canopy area) to other morphological or physiological plant characteristics (Niklas 1994). Allometric relations have been found in a broad variety of plant species which include relationships between height and girth (Abbott 1985) and between fruit size and seed mass (Shipley & Dion 1992). Plant girth has been shown in some species to reflect plant reproductive maturity. *B. grandis* for example becomes reproductive at mean diameter at breast height (DBH) of 4-5 cm and fruit successfully at mean DBH of 6-7 cm (Abbott 1985). However, given the difference in biology between each species selected in this study, the significance of each biological characteristic in terms of the number of infructescences is also different. For *B. sessilis* the number of infructescences available was strongly correlated with morphological characteristics, with canopy area (r^2 = 0.90) showing the highest coefficient of determination. In comparison to *B. attenuata* and *B. menziesii, B. sessilis* commonly occurs in pure stands with a large number of stems and at high density. This obligate reseeder produces large amounts of seed which leads to an increase in number of stems m^{-2}. Therefore it is not surprising that the number of infructescences available for *B. sessilis* displayed strong allometric relationships with each factor measured as plant size within stands is very uniform.

Although *B. sessilis* models displayed high correlation coefficients, this trend was not shown for *B. attenuata* and *B. menziesii*. The models for *B. attenuata* and *B. menziesii* revealed the strongest relationships with canopy volume and canopy area, however these variables when analysed individually accounted for < 23% of the variability in the number of infructescences. Multiple linear regression models involving all *B. attenuata* and *B. menziesii* plant morphological variables increased the correlation coefficients, however the models are less reliable than those revealed for *B. sessilis*. The reason for this is most likely due to the different methods of reproduction. *B. attenuata* and *B. menziesii* are both resprouters and can regenerate from both seed and epicormic buds. As a consequence disturbance such as fire which kills obligate reseeders does not

generally kill resprouters. Therefore, *B. attenuata* and *B. menziesii* are often found in stands of differing aged individuals, compared to obligate reseeders which are uniform in age and structure. This increased variability in tree size impacts on the number of infructescences and therefore the predictive capacity of modelling.

Previous studies on *Banksia* phenology have primarily focused on flowering times as opposed to the timing of infructescence maturation. Understanding seasonal fluctuations in infructescence development for *Banksia* species is essential in the management of habitat for Carnaby's cockatoos. Trend-lines for each *Banksia* species for infructescences drying appear to vary considerably in comparison to total number of infructescences. External factors appear to be influencing infructescence numbers. The most likely reason for this would be from predation, such as feeding pressures from Carnaby's cockatoo's. Five out of the six *Banksia* species reached peak infructescence maturation in December highlighting the importance of *B. attenuata* as a food source in banksia woodlands. Infructescence maturation timing also identifies *B. sessilis* as an important food resource as it is available for a longer period of time than other *Banksia* species, peaking in December but available in large numbers through to June. The combination of *B. attenuata* and *B. sessilis* infructescence maturation timing provides food resources throughout the year.

Understanding the predicted response of plants to external factors and relationships between structural and functional plant characteristics is essential for determining the amount of food available for threatened species such as the Carnaby's cockatoo. The identification of morphological predictors of infructescence numbers has provided information which can be used to identify important feeding habitats to help manage and conserve the cockatoos. This study has improved our understanding of the factors that influence the production of banksia infructescences in proteaceous woodlands. Further research on the consumption and energetic reward from banksia food sources in later chapters (Chapters 5 and 6) should assist in ranking the importance of each *Banksia* species as a food resource.

Chapter 5: Banksia infructescence consumption by Carnaby's cockatoo on the Swan coastal plain

Introduction

Carnaby's cockatoo is a threatened species endemic to South Western Australia (Wildlife Conservation Act 1950; Environment Australia 1999) where they forage on a diverse array of food resources both native and exotic, consisting of 130 plant species from 21 families (Groom 2010 & references there in). Proteaceous species contribute over half of the Carnaby's cockatoo diet of which 95% is attributed to *Banksia, Grevillea* and *Hakea* species (Groom 2010; Chapter 3). In particular *Banksia* species form a characteristic component of the birds' diet (Saunders 1980: Shah 2006; Valentine & Stock 2008; Chapter 3). On the Swan coastal plain *B. attenuata, B. menziesii, B. grandis, B. ilicifolia, B. prionotes* and *B. sessilis* have been identified as the most important banksia food plants (Saunders 1980; Shah 2006; Valentine & Stock, 2008; Chapter 3).

The genus *Banksia* is distributed across the South Western Province and eastern and northern coastal margins of Australia, with one species occurring outside of Australia (Mast 1998). As a result *Banksia* forms a characteristic genus in the South Western Province of Australia (Speck 1958), and in which the greatest concentration (George, 1984) and endemism (Lamont & Connell, 1996) of species exists. Banksias provide seed and nectar food resources for a variety of birds (Whelan & Burbidge 1980; Saunders 1980; Shah 2006; Valentine & Stock 2008), invertebrates (Clifford and Drake 1981, Scott & Black 1981) and mammals (Rourke & Wiens 1977; Carpenter 1978). Invertebrates attracted to banksia inflorescences and woody structures are also fed on by a range of animals (Whelan & Burbidge 1980; Scott & Black 1981: van Leeuwen & Lamont 1996). Carnaby's cockatoos feed on all three food resources provided directly (seed and nectar) and indirectly (insect invertebrates) by *Banksia* species, which make this genus highly valued (Saunders 1980: Shah 2006; Valentine & Stock 2008). However, the true value of each *Banksia* species as a food source for Carnaby's cockatoos is unknown.

To understand the importance of *Banksia* species as a food resource for Carnaby's cockatoos an investigation was undertaken to identify temporal variability in infructescence usage and consumption rates under different environmental conditions across the Swan coastal plain. Due to the difficulties in quantifying inflorescence food resource usage (nectar and or invertebrates) by Carnaby's cockatoos only

infructescences were considered in this study. Systematic surveys were conducted throughout 2011 which examined foraging signs left behind by Carnaby's cockatoos following feeding bouts. Discarded infructescences were analysed for signs of grubbing for insect larvae and seed extraction. Additionally, infructescence consumption rates by Carnaby's cockatoos were compared to available resources in banksia stands of varying post-fire ages and in the presence and absence of *Phytophthora cinnamomi* to identify whether utilisation of food resources varied across the landscape in relation to these factors.

Study Site

This study was undertaken across the Swan coastal plain from south of Guilderton (31° 20' S) to the southern boundary of Waroona Shire (32° 55′ S). The area is bounded by the Indian Ocean to the west and Darling Scarp (116° 02' E) to the east. Situated on the western edge of Australia the study area covers an area of 5 075 km^2, approximately 170 km in length and 25 km wide. The Swan coastal plain is a low lying plain dominated by nutrient-poor soils (McArthur & Bettenay 1960) that experiences a mediterranean climate with an annual rainfall of 600-1 000 mm (Beard 1984).

Methods

Study sites were selected across the Swan coastal plain in banksia dominated woodlands. Coastal, wetland and transition vegetation zones were excluded from site selection. Eighty-four 20 m x 20 m quadrats were established across 21 sites. Sites were select to represent a variety of landform types, time since last fire, health conditions and banksia communities. A minimum of three representative quadrats were established within each of the 21 sites, for each selected landform type, time since last fire, health condition and banksia community. Quadrats were marked by inserting fence droppers in each corner.

Banksia species identified in Chapter 3 as Carnaby's cockatoo food sources were targeted in this study, which include *B. attenuata, B. grandis, B. ilicifolia*, *B. menziesii, B. prionotes* and *B. sessilis.* Surveys were conducted bi-monthly from February to December 2011, resulting in six collection periods in total. Carnaby's cockatoos are destructive feeders, removing plant parts with strong beaks by holding them in their left foot while extracting seed and larvae, and discarding residues on the ground. The surveys measured feeding residues by recording the number of eaten and uneaten infructescences on the ground. Any infructescence that had a mark that appeared to

have been made by a Carnaby's cockatoo was classified as eaten, ranging from completely torn apart, to structures with only one chew mark present. Uneaten infructescences were those that only appeared to have chew marks on the stem with no obvious signs of seed or insect larvae extraction from the infructescence itself. Feeding residues were removed from quadrats after each survey to ensure that only new feeding signs were counted in subsequent surveys.

To ensure feeding residues were not missed or overlooked due to dense understorey vegetation, small flags were used to mark out 5 m x 5 m quadrats nested within the 20 m x 20 m quadrat. Each nested quadrat was surveyed systematically, whilst being mindful to minimise disturbance to understorey vegetation. For *B. sessilis* stands an alternative method was used due to the high density of stems and differences in infructescence morphology from other species of *Banksia*. Three 2 m x 2 m nested quadrats were randomly established within the larger 20 m x 20 m quadrat. Two 0.5 m x 0.5 m residue trays were placed in the nested quadrats to collect discarded infructescences. Two residue trays were also placed in quadrats where density of *B. sessilis* stems were low and the results scaled up by a factor proportional to the total canopy area that *B. sessilis* contributed for that site.

To establish the numbers of infructescences available as a food resource, the numbers of drying infructescences which make up the standing crop in the tree canopy were recorded at the end of the survey period using Bell and Stephens (1984) *Banksia* reproductive phenophases. This information was combined with Carnaby's cockatoo feeding residues recorded over the 12-month survey period to determine the amount of banksia food available. Infructescence consumption in relation to availability was compared in the presence and absence of *P. cinnamomi* and between various post-fire age stands to identify the influence of external factors on consumption (for *P. cinnamomi* disease and time since last fire methodologies refer to Chapter 4).

Prior to analyses, data were screened for normality and equality of variance, SPSS version 18 was used for all analyses. The influence of *P. cinnamomi* was tested between sampling pairs (disease site vs. non disease site in a common locality). Data were not normally distributed so Kruskal-Wallis tests were conducted for *B. attenuata* and *B. menziesii* with a factor of *P. cinnamomi* presence and dependent variable of percentage of infructescences consumed by Carnaby's cockatoo. Analyses of time since last fire were also analysed using Kruskal-Wallis tests as it was not possible to transform data to be normally distributed. Due to the variability in the number of stems

per quadrat and small quadrat sample size for *B. sessilis,* in relation to time since last fire, only three fire categories were analysed (≤ 5, 6-15 and ≥ 16 years post-fire). Five categories for time since last fire were used for *B. attenuata* and *B. menziesii* stands (≤ 5, 6-10, 11-15, 16-20 and ≥ 21 years post-fire).

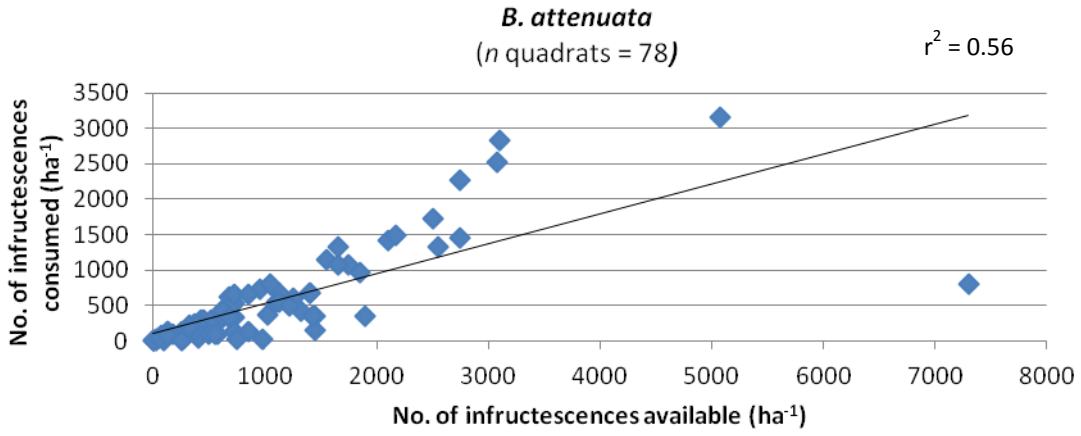
Results

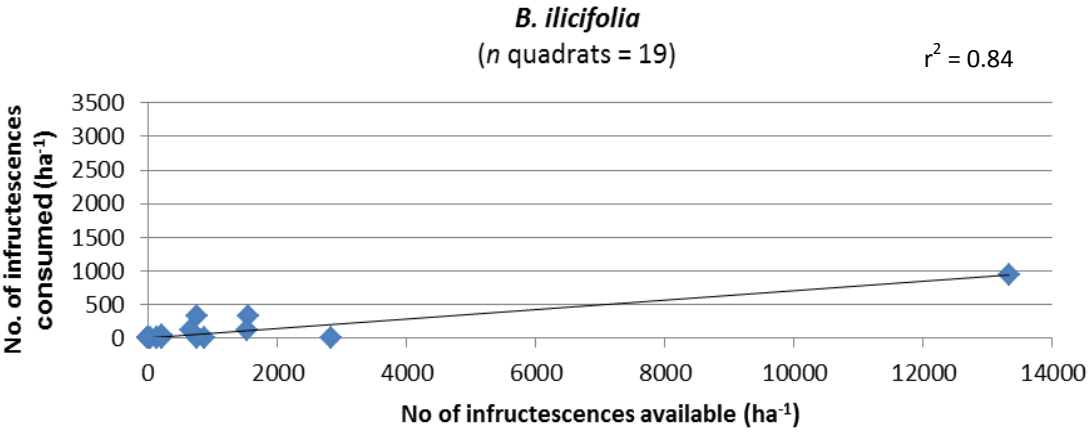
Approximately 50% of drying banksia infructescences were handled by Carnaby's cockatoos throughout the year, with around 80% of these consumed (Table 5.1). *B. grandis* (86%) and *B. sessilis* (85%) had the highest percentage of handled infructescences consumed for seed by Carnaby's cockatoo, while *B. ilicifolia* (51%) was the lowest. *B. attenuata* and *B. menziesii* were the only species to record >15% of infructescences consumed for larvae extraction, with *B. attenuata* (34%) double that of *B. menziesii* (16%).

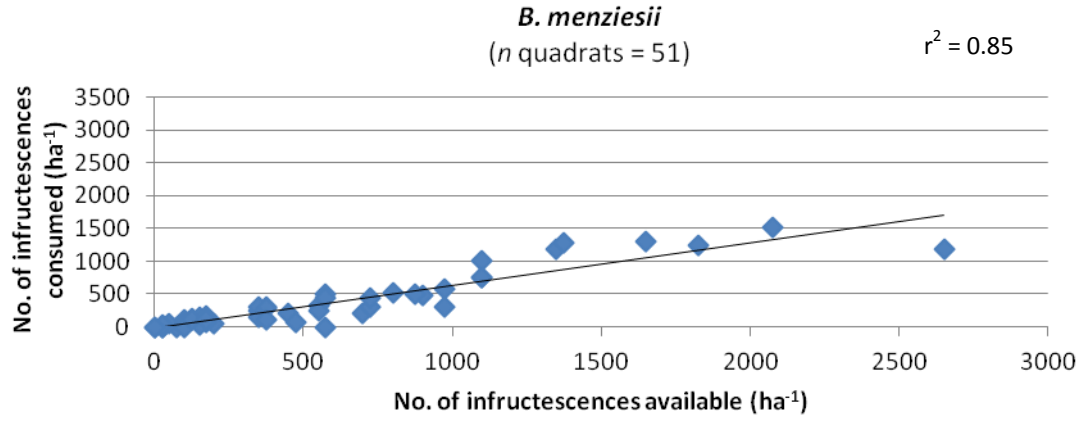
Table 5.1: Total number of infructescences available, handled and consumed by Carnaby's cockatoo (ha^{-1}) over 12-months.

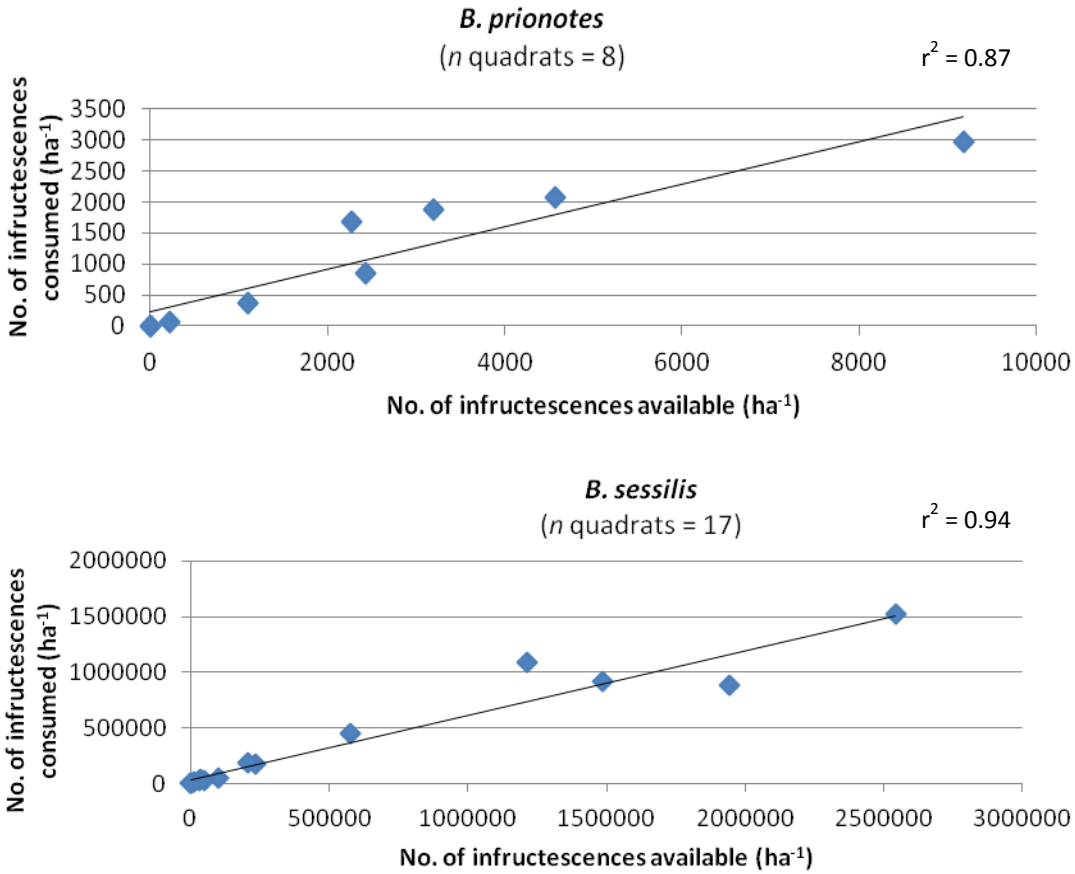
	B. attenuata	*B. grandis*	*B. ilicifolia*	*B. menziesii*	*B. prionotes*	*B. sessilis*
n sites (total of 1200m^2 each)	27	7	11	21	5	10
n reproductive stems (ha^{-1})	337.96	11.90	39.39	200.40	1 246.67	3 255.00
n infructescences available (ha^{-1})	989.81	14.29	693.94	464.29	1 516.67	281 327.50
n infructescences handled (ha^{-1})	644.44	8.33	110.61	367.06	803.33	211 506.67
n infructescences consumed (ha^{-1})	512.65	7.14	57.58	290.08	648.33	178 970.83
% of available infructescences handled	65	58	16	62	53	75
% of available infructescences consumed	52	50	8	62	43	64
% of handled infructescences consumed	80	86	52	79	81	85
% of handled infructescences consumed for seed only	46	86	51	64	71	85
% of handled infructescences consumed for larvae only	22	0	1	9	5	0
% of handled infructescences consumed for both seed and larvae	12	0	0	7	4	0

Regression analysis of the number of infructescences available and the number of infructescences consumed revealed strong linear associations for each species (Figure 5.1 – 5.5). *B. attenuata* recorded the lowest correlation coefficient ($r^2 = 0.56$), but removal of the outlier that recorded 7 300 infructescences ha^{-1} available and 800 infructescences ha^{-1} consumed the correlation coefficient increased to 85%. *B. grandis* was not investigated due to the low number of infructescences recorded.









Figures 5.1 – 5.5: Regression analysis of the number of infructescences available and the number consumed by Carnaby's cockatoo for each *Banksia* species ha^{-1}. Note the y-scale change for *B. sessilis*.

The influences of *P. cinnamomi* and time since last fire were examined to determine if feeding activity was driven by infructescence availability or site condition (Tables 5.2 & 5.3). Consumption was found to be related to infructescence availability rather than site condition. No statistically significant differences ($P > 0.05$) were found for *B. attenuata* and *B. menziesii* for percentage of infructescences consumed in the presence or absence of *P. cinnamomi* (*B. attenuata* $k_{[1]} = 0.445$, $P = 0.505$, n = 14; *B. menziesii* $k_{[1]} = 0.605$, $P = 0.437$, n = 9). With respect to time since last fire no statistically significant difference ($P > 0.05$) was found for *B. attenuata* ($k_{[4]} = 6.057$, $P = 0195$, n = 72). The percentage of infructescences consumed significantly differed ($P < 0.05$) for *B. menziesii* ($k_{[4]} = 9.564$, $P = 0.048$, n = 51) and *B. sessilis* ($k_{[2]} = 10.804$, $P = 0.005$, n = 17). However, to account for the delay in post-fire infructescence development stands < 5 years post-fire were removed for the *B. menziesii* and the *B. sessilis* analyses. Removal of these young stands resulted in no significant differences (> 0.05) between the percentages of infructescences consumed by Carnaby's cockatoos (*B. menziesii* $k_{[3]} = 1.525$, $P = 0.677$, n = 46; *B. sessilis* $k_{[1]} = 1.297$, $P = 0.255$, n = 12) in relation to time since last fire.

Table 5.2: Percentage of available infructescences consumed by Carnaby's cockatoo in the presence and absence of *P. cinnamomi*.

Species	*P. cinnamomi* (PC)	*n* quadrats (400 m^2)	% of infructescences consumed (mean ± SE)
B. attenuata	PC	5	59 ± 0.12 ^{NS}
	Non PC	9	50 ± 0.07
B. ilicifolia	PC	2	0
	Non PC	3	13 ± 0.67
B. menziesii	PC	3	58 ± 0.17 ^{NS}
	Non PC	6	73 ± 0.61

NS = No significance at 5% level

Table 5.3: Percentage of available infructescences consumed by Carnaby's cockatoo with regards to time since last fire.

Species	Fire age (years)	Category	*n* quadrats (400 m^2)	% of infructescences consumed (mean ± SE)
B. attenuata	≤ 5	1	8	34 ± 0.12
	6-10	2	9	41 ± 0.10
	11-15	3	12	58 ± 0.06
	16-20	4	8	54 ± 0.12
	≥ 21	5	32	56 ± 0.05
B. menziesii	≤ 5	1	5	15 ± 0.08
	6-10	2	3	51 ± 0.21
	11-15	3	9	65 ± 0.08
	16-20	4	8	50 ± 0.11
	≥ 21	5	23	60 ± 0.06
B. sessilis	≤ 5	1	5	04 ± 0.04
	6-15	2	5	57 ± 0.10
	≥ 16	3	7	78 ± 0.07

Note: *P. cinnamomi* quadrats removed.

There was significant temporal variability in infructescence use throughout the year (Figure 5.6) with the greatest number of infructescences used between April and September. Carnaby's cockatoos showed flexibility in diet, incorporating dietary switching between *Banksia* species throughout the year (Figure 5.6). Consumption of infructescences from *B. grandis* (< 1%) was small and therefore not investigated further. *B. attenuata* infructescence consumption was highest from June to September, with just over 30% of all infructescences consumed, and lowest between the February and April sampling periods (< 10% consumed). *B. menziesii* infructescence consumption was more even throughout the year compared with *B. attenuata.* However, there was a decrease in infructescence use in April, dropping to 6% of the total with around 18% infructescence consumption in the collection period prior to and

after April. Peak infructescence consumption period for *B. menziesii* (> 25%) occurred from August to September. *B. ilicifolia* peak consumption also occurred in August to September. *B. prionotes* infructescence consumption peaked from April to May representing 34% of total consumption. Similar to *B. menziesii, B. prionotes* consumption dropped in the April collection period with only 7% consumed compared with 15% two months earlier. *B. sessilis* peak consumption was recorded from April to July with just over 60% of infructescences consumed. February and December collection months contributed < 10% of the total *B. sessilis* infructescence consumption.

B. attenuata and *B. menziesii* were the only species to have > 10% of infructescences handled by Carnaby's cockatoo for larvae (Table 5.4). Although grubbing was observed in *B. ilicifolia,* its incidence in the species was low. Peak larvae extraction occurred in August and September for *B. attenuata, B. menziesii* and *B. prionotes* (Table 5.4).

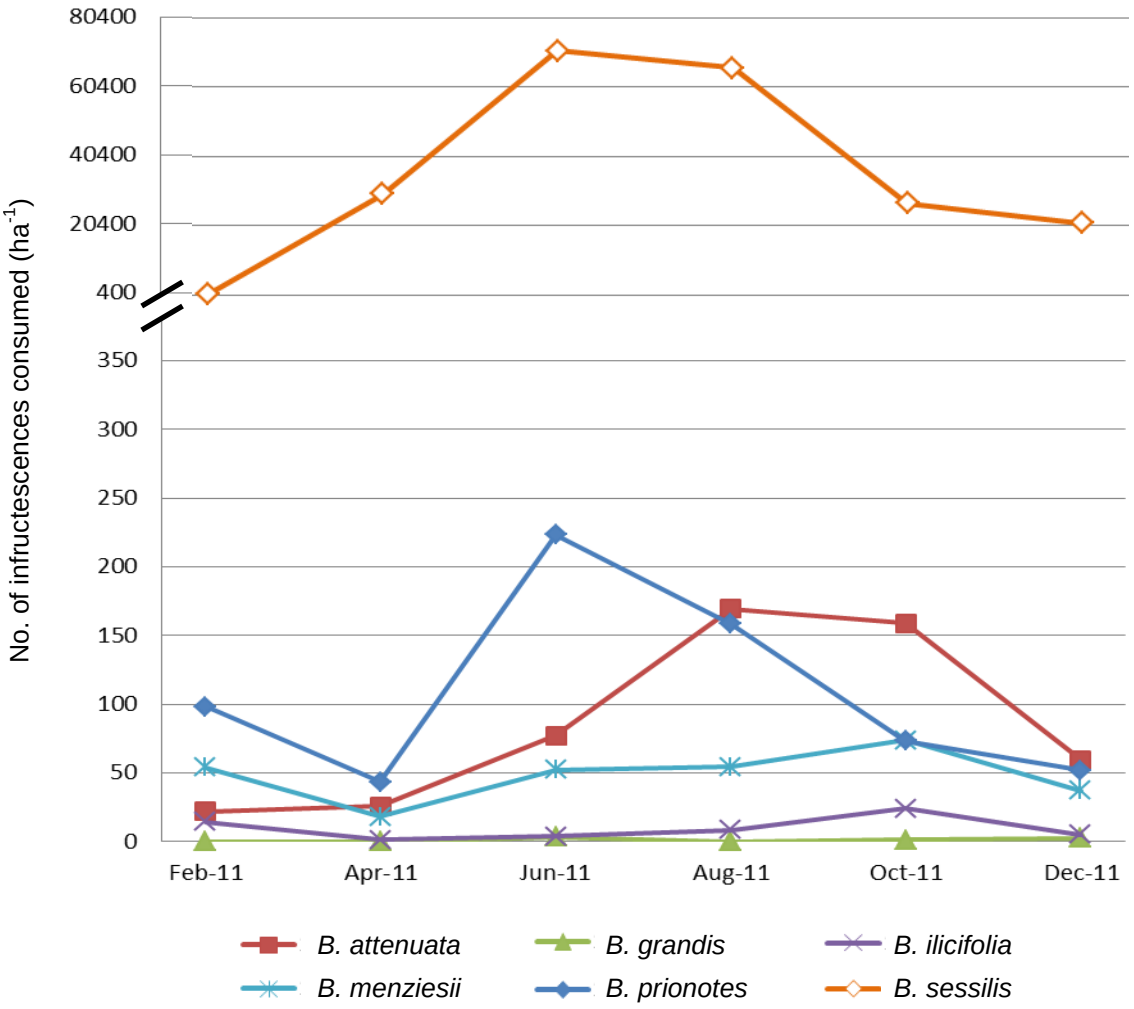


Figure 5.6: Seasonal consumption of *Banksia* infructescences for seed and/or larvae ha^{-1} by Carnaby's cockatoo across the Swan coastal plain. Note the scale change for the number of infructescences consumed for *B. sessilis.*

Table 5.4: Total number of banksia infructescences ha^{-1} consumed for invertebrate larvae by Carnaby's cockatoo during each sample period.

Species	Feb-11	Apr-11	Jun-11	Aug-11	Oct-11	Dec11	Total
B. attenuata	2.47	10.80	35.80	63.89	68.83	35.19	216.78
B. menziesii	0.80	2.38	7.14	13.10	20.63	12.70	56.75
B. prionotes	15.00	1.67	16.67	10	25	6.67	75.01
B. ilicifolia	0.00	0.00	0.00	0.00	0.00	0.83	0.83

Discussion

This study demonstrates the strength of association between banksia infructescence availability and consumption by Carnaby's cockatoos on the Swan coastal plain. Over a 12-month period, Carnaby's cockatoos handled around half of the available drying banksia infructescences, of which over three quarters were consumed. Carnaby's cockatoo showed flexibility in diet, with temporal variability in infructescence use throughout the year incorporating dietary switching between *Banksia* species. *B. attenuata* and *B. sessilis* were frequently handled and consumed due to the large number of infructescences available, highlighting their importance as a food resource for Carnaby's cockatoos.

The Swan coastal plain forms an important non-breeding feeding ground for Carnaby's cockatoo from December to July (Saunders 1980). The level of body condition acquired by an individual during the non-breeding season for some species has been suggested to be closely linked to breeding success (Monaghan *et al.* 1989; Naulleau & Bonnet 1996), including Carnaby's cockatoos (Berry & Owen 2010). Critical banksia infructescence use by Carnaby's cockatoos occurred between April and September. Interestingly, extraction of larvae in *B. attenuata* and *B. menziesii* showed a gradual increase in consumption peaking in the October sample period (August-September). Larvae consumption in *B. prionotes* also peaked August-September but was more variable. Over 30% of infructescences manipulated for larvae for each *Banksia* species were recorded during this period. Whether this is a function of insect biology, infructescence maturation or the birds breeding requirements needs further investigation.

Despite Carnaby's cockatoo being a seasonally migratory species for breeding purposes, this study recorded banksia infructescence use throughout the year. This year-round food supply supports the cockatoos visiting the coastal plain. However, there was a clear drop in infructescence consumption between the October and

December collection period, with an increase observed during the February sample period. This result is consistent with published observations of migration breeding behaviour and changes in local cockatoo population size at those times of year. Therefore recorded infructescence consumption during the October and December surveys is most likely attributed to non-breeding birds which stayed on the Swan coastal plain during the breeding season.

Feeding intensity varied throughout the year, with a noticeable drop recorded for three out of the five *Banksia* species during the April sampling period. The most reasonable explanation is an increase in the availability of other non-*Banksia* food resources, rather than a reduction in banksia infructescence availability. The peak cone consumption of exotic Maritime Pine, *Pinus pinaster,* by Carnaby's cockatoos occurs between January and June, with little to no availability or consumption during the rest of the year (Stock *et al.* 2013 Although pine plantations in the study area only cover 175 km², compared to 1 359 km² for potential remnant vegetation feeding resources, pines are planted in monocultures which produce a large number of cones that require little effort or energy to acquire. Maritime Pine seed has become an important alternative food resource for Carnaby's cockatoos (Perry 1948; Saunders 1974, 1980; Finn *et al.* 2009) and for which energy content is slightly higher than any native Proteaceous species (Stock *et al.* 2013).

Many species distribute themselves in response to an increase in available food resources (Johnson & Sherry; Banko *et al.* 2002, Macreadie *et al.* 2010). Carnaby's cockatoos respond to the standing crop of banksia infructescences, with consumption rates closely related to availability. As infructescence availability of each *Banksia* species changes during the year (Chapter 4), the level of consumption changes accordingly. In the presence of *P. cinnamomi,* infructescence consumption by Carnaby's cockatoos remains proportional to reduced availability. Similarly, infructescence consumption rates, in relation to time since last fire, were also related to infructescence availability. Although *B. menziesii* and *B. sessilis* woodlands ≤ 5 years post-fire showed a significantly ($P < 0.05$) lower consumption rate of infructescences by cockatoos in relation to the numbers available, the removal of these sites from analysis showed no significant differences between the percentage of infructescences consumed for each fire age. *B. menziesii* and *B. sessilis* infructescences mature later after fire than *B. attenuata* infructescences. Young fire sites (≤ 5 years post-fire) only started to produce *B. menziesii* and *B. sessilis* infructescences for the first time late in the survey period. Therefore, infructescences were not available throughout the survey

period as a food resource for Carnaby's cockatoos. When infructescences did begin to mature, total consumption was low in comparison to availability based on total standing infructescence counts conducted in December 2011. This was most likely a direct result of the survey period (December) coinciding with the cockatoo's breeding season and the reduced number of birds on the Swan coastal plain. Infructescence consumption by Carnaby's cockatoos significantly ($P < 0.05$) increased in stands where time since last fire exceeded 6 years.

As well as consuming infructescences standing in the tree canopy, Carnaby's cockatoos have been observed foraging on the ground (Valentine & Stock 2008; Stock *et al.* 2013). In this study feeding residues including infructescences uneaten were removed from each quadrat bi-monthly, removing a potential future food resource. Given that Stock *et al.* (2013) observed Carnaby's cockatoos foraging on the ground in more than half of their sample points the proportion of infructescences consumed during this study may actually be higher than was recorded by this study. Further investigation through observation of the Carnaby's cockatoo feeding behaviour is required to resolve this issue.

It is also important to note, that although the numbers of available infructescences for each species were counted, the availability of the seed in those infructescences was not investigated. All infructescences may not be equally available as might be assumed from a simple count (Hutto 1990). A number of infructescences counted, that formed part of the standing crop, may not be available to the birds as seed may have been aborted during development or predated by insect invertebrates. We lack a bird's perception and therefore do not know if some infructescences had been assessed/screened previously by the birds and rejected as a suitable food resource (e.g. knocked/tapped to determine viability through sound). Due to mechanical and perceptual differences between anthropocentric sampling techniques and a bird's observation or ecology, resources will be sampled differently (Robinson *and* Holmes 1982; Heinrich & Collins 1983; Sherry 1984).

One of the principal views on the optimal foraging theory is that organisms should maximise net energy intake (Lack 1954). An example of this is the glossy black-cockatoo *Calyptorhynchus lathami* which maximises food intake per unit of foraging time by foraging in trees with higher numbers of infructescences and seed yields (Chapman & Paton 2006). Glossy black-cockatoos selectively forage in large trees, reducing the number of movements made between plants which consequently reduces

energy expenditure (Chapman & Paton 2006). Given Carnaby's cockatoos and glossy black-cockatoos are related, Carnaby's cockatoo may select certain banksia trees, infructescences and/or sites over others more frequently due to the bird's observation of net energy gain. This may be the reason birds' shift from banksia to pine during peak maturation periods as net energy gain is greater. This theory is supported by the findings in this study that showed a decline in banksia use recorded in April which coincided with peak *P. pinaster* cone consumption (Stock *et al.* 2013). Increased feeding intensity by Carnaby's cockatoo was also observed where *B. sessilis* occurred in stands with high stem densities. Fluctuations in feeding intensity between food resources by Carnaby's cockatoo suggest that plants which produce a large number of infructescences and which are in close proximity to one another (e.g. plantations or thickets), may be more valuable as a food resource since net energy intake per unit feeding time is maximized compared to plants that produce fewer seeds spread over larger areas (e.g. *B. attenuata* and *B. menziesii* woodlands). However the pattern of food resource consumption was most likely a consequence of availability, as noted by the strong linear relationships between the numbers of banksia infructescences available and infructescence consumption (Figures 5.1 – 5.5) and the temporal variability in infructescence use of each *Banksia* species throughout the year (Figure 5.6). Despite habitat heterogeneity, such as post-fire age and presence of *P. cinnamomi*, consumption levels were consistent with infructescence availability, suggesting Carnaby's cockatoos were exploiting all available resources across the landscape.

As noted in Chapter 3, *Banksia* species form a characteristic component of the Carnaby's cockatoo diet. The importance of banksias as a food resource and the widespread distribution of the genus across the South Western Province allows Carnaby's cockatoos to radiate throughout this region, utilising available resources throughout the year. This study has quantified the relationship between banksia infructescence availability and infructescence consumption by Carnaby's cockatoo. Greater understanding of this relationship has highlighted the birds' food resource requirements which will prove useful in the management and conservation of suitable feeding habitat for the Carnaby's cockatoo through habitat assessment.

Chapter 6: Seed reward of *Banksia* species on the Swan coastal plain for Carnaby's cockatoo

Introduction

Understanding how food availability and foraging ecology influence the abundance and distribution of the endemic Carnaby's cockatoo is critical for conservation management planning for the species. The efficacy of any management plan to conserve Carnaby's cockatoos will depend on accurate information on population fluctuations associated with food resource usage which is likely to be linked to the reward associated with different food resources. Food resource availability (and the associated rewards) can be influenced by threats to habitat caused by clearing (urban development and agriculture), fire and disease (*P. cinnamomi*) (Chapter 4) across the birds range. For example, the extent of suitable habitat (feeding, breeding and roosting) in the known range of Carnaby's cockatoo (Murchison – Esperance) is estimated at approximately 17 000 km^2, 45% less than the pre-European estimate of 38 000 km^2 (E. Rice, DEC GIS, pers. comm. April 4 2010). On the Swan coastal plain (Perth coastal bioregion - Interim Biogeographical Regionalisation of Australia), remnant vegetation has been reduced by 43% to under 4 740 km^2 (J. Kinloch, DEC GIS, pers. comm. October 2012) with urban development along the Swan River and adjoining coastline increasing by 452 km^2 between 1974 and 2008 (Western Australian Planning Commission 2012).

Foraging habitat for Carnaby's cockatoos can be quantified by measuring the energetic content of important seed resources, determining the number of seeds available and establishing the number of infructescences consumed by the birds'. Seed is highly digestible (80-95%), therefore energy content closely resembles energy gain (Withers 1982; Earle & Clarke 1991), making it relatively easy to assess potential energy consumption of species such as the Carnaby's cockatoo. Proteaceae species possess seeds rich in protein, oil and other essential nutrients (van Staden & Comins 1976; van Staden & Brown 1977; Lott & Buttrose 1978; Kuo *et al.* 1982; Pate *et al.* 1985), making them an important food resource for Carnaby's cockatoos. In particular, *Banksia* species were identified in Chapter 3 as important food resource plants, although the level of importance was not established. Research by Cooper *et al.* (2002) and Stock *et al.* (2013) measured the energetic content of a variety of plant species consumed by Carnaby's cockatoo, including a number of *Banksia* species, and calculated the number of seeds and infructescences required to meet the birds daily field metabolic rate (726 kJ). However, the average number of seeds per follicle and follicles per

infructescence were not fully examined. Therefore, the calculations on the number of infructescences required to meet the bird's daily metabolic requirements is likely to be underestimated.

This study was designed to refine our understanding of the relationship between Carnaby's cockatoo feeding ecology and the energetic yield of seed of six *Banksia* species found on the Swan coastal plain. The objectives of this study were to determine:

- the number of banksia follicles and infructescences consumed for seed and insect larvae by Carnaby's cockatoos;
- the number of follicles per infructescence and number of seeds available per follicle;
- the energy content of seed from each *Banksia* species; and
- the number of infructescences required to meet the daily energy requirements for Carnaby's cockatoo.

It is intended that knowledge of the birds' feeding efficiency with respect to metabolic requirements and seed resource availability will assist in identifying the amount of food resources needed to sustain Carnaby's cockatoo, which can then be incorporated into management plans to protect adequate areas of suitable feeding habitat.

Study Site

This study was undertaken across the Swan coastal plain, south of Guilderton (31° 20' S) to the southern boundary of Waroona Shire (32° 55′ S), bounded by the Indian Ocean to the west and Darling Scarp (116° 02' E) to the east. Situated on the western edge of Australia, the study area covers an area of 5 075 km^2 (approximately 170 km in length and 25 km wide). The Swan coastal plain is a low lying plain dominated by nutrient-poor soils (McArthur & Bettenay 1960) and experiences a mediterranean climate with an annual rainfall of 600-1 000 mm (Beard 1984). Banksia woodlands form a dominant vegetation component on the Swan coastal plain (Heddle *et al.* 1980; Beard 1984; Gibson *et al.* 1994).

Methods

Study sites were selected across the Swan coastal plain in banksia dominated woodlands. Coastal, wetland and transition vegetation zones were excluded from site selection. Eighty-four 20 m x 20 m quadrats were established at 21 bushland sites.

Sites comprised a variety of landform types, time since last fire, health conditions and banksia communities. Three representative quadrats were established within each of the 21 sites for each selected landform type, time since last fire, health condition and banksia community. Quadrats were marked by inserting fence droppers in each corner.

Feeding residues were collected and recorded between December 2010 and December 2011. Feeding residues which included the number of eaten and uneaten infructescences that appeared to have been pruned from parent plants were collected and recorded for each quadrat. For *B. sessilis* stands an alternative method was used due to the high density of stems and differences in infructescence morphology from other species of *Banksia*. Three 2 m x 2 m nested quadrats were randomly established within the larger 20 m x 20 m quadrat. Two 0.5 m x 0.5 m residue trays were placed in the nested quadrats to collect discarded infructescences and follicles Two residue trays were also placed in quadrats where density of *B. sessilis* stems were low and the results scaled up by a factor proportional to the total canopy area that *B. sessilis* contributed for that site. The proportion of follicles closed, opened naturally, destroyed by insect larvae, seed and larvae extracted by Carnaby's cockatoos were recorded for each infructescence collected.

Seed morphology was investigated for each *Banksia* species to determine the proportion of intact seed (firm) versus non intact seed (aborted) in fully developed follicles. Ten infructescences were harvested from banksia plants within a 50 m radius surrounding all non *P. cinnamomi* infected quadrats. At sites with low infructescence production, infructescences were collected further afield where necessary (same soil type, post-fire age and vegetation assemblage), or if this was not possible a smaller number of infructescences were collected. Infructescences were fumigated for insects, dry stored for four months and then oven dried for 30 min at 200°C in a conventional fan forced oven to assist follicle opening. Seeds were removed by hand with the aid of tweezers and secateurs where necessary. Seeds removed from infructescences were tested for firmness by hand. Seed that was paper-like, thin, transparent and flexible was classified as aborted while seed that was hard, dense and inflexible was classified as firm (Enright & Lamont 1989; Witkowski *et al*. 1991).

The energy content for *B. attenuata, B. grandis* and *B. sessilis* seeds were derived from research conducted by Cooper *et al.* (2002) and Stock *et al.* (2013). To determine the seed energy content of *B. menziesii* and *B. prionotes,* seeds were bombed using a Gallenkamp ballistic bomb calorimeter. Five grams of seed from each species were

first dehusked using a scalpel, weighed to ± 0.0001 g with a Mettler® Toledo scale, and dried in a convection oven at 47°C to constant weight. Oven-dried seeds were then ground into a fine powder which was compressed into a pellet, re-dried, weighed and the energy content measured using the bomb calorimeter calibrated with benzoic acid. Six replicates were each measured for *B. menziesii* and *B. prionotes*.

The mean dry seed weight for each of the six *Banksia* species dominant on the Swan coastal plain were determined by randomly selecting and weighing firm seeds extracted from a range of infructescences from across all study sites. The information on *Banksia* species seed weight and energetic yield were used in conjunction with information on the birds' field metabolic rate estimated by Cooper *et al.* (2002) to determine the number of infructescences required to meet the daily field energy requirements of Carnaby's cockatoo (726 kJ d^{-1}).

Results

Over 50% of intact infructescences (follicles counted) were manipulated for seed and larvae for all species (Table 6.1). *B. sessilis* recorded the largest number of infructescences handled (244 042) and follicles (181 260) manipulated by Carnaby's cockatoos for seed. Carnaby's cockatoos selected a larger number of infructescences and follicles of *B. sessilis* over comparatively fewer sites than for *B. attenuata* and *B. menziesii* (number of sites four and three times greater respectively). The percentage of *B. grandis, B. ilicifolia* and *B. menziesii* follicles manipulated for seed ranged from 40-52%, whereas, *B. attenuata* (22%) and *B. prionotes* (26%) recorded lower figures (Table 6.2). *B. attenuata* had the highest percentage of follicles closed (27%), with all other species recording < 15% of follicles closed. Sixty-two percent of *B. prionotes* follicles were naturally open. *B. attenuata, B. grandis*, *B. ilicifolia* and *B. menziesii* averaged around 44% of follicles open, whereas *B. sessilis* recorded < 6%. Less than 7% of banksia follicles were destroyed by insect larvae. *B. attenuata, B. menziesii* and *B. prionotes* recorded evidence of insect larvae extraction by Carnaby's cockatoo however the mean number of follicles per infructescence extracted for larvae was < 1% for each species.

Table 6.1: Number of infructescences selected by Carnaby's cockatoo and the number of follicles selected by Carnaby's cockatoo (ha^{-1}) for seed or larvae, closed, opened naturally and destroyed by insect larvae.

	B. attenuata	*B. grandis*	*B. ilicifolia*	*B. menziesii*	*B. prionotes*	*B. sessilis*
n infructescences handled (ha^{-1})	644.44	8.33	110.61	367.06	803.33	211 506.67
n infructescences with feeding activity (ha^{-1})	512.65	7.14	57.58	290.08	648.33	178 970.83
n infructescences shredded by Carnaby's for larvae (not included in follicle count) (ha^{-1})	95.06	0.00	0.76	16.67	26.67	0.00
Total n follicles (ha^{-1})	6 348.46	469.05	147.73	2 175.40	20 620.00	223 276.67
Follicles with seed extracted (ha^{-1})	1 406.48 (22%)	242.86 (52%)	68.18 (46%)	880.16 (40%)	5 418.33 (26%)	181 259.17 (81%)
Follicles damaged, seed not removed (ha^{-1})	52.16 (<1%)	0.00 (0%)	0.76 (<1%)	22.62 (1%)	58.33 (<1%)	3 677.50 (2%)
Follicles with larvae extracted (ha^{-1})	103.70 (2%)	0.00 (0%)	0.00 (0%)	21.03 (1%)	6.67 (<1%)	0.00 (0%)
Follicles closed (ha^{-1})	1 686.42 (27%)	1.19 (<1%)	9.85 (7%)	215.48 (10%)	2 076.67 (10%)	22 611.67 (10%)
Follicles open (ha^{-1})	2 786.42 (44%)	217.86 (46%)	64.39 (43%)	957.14 (44%)	12 861.67 (62%)	12 016.67 (5%)
Follicles destroyed by invertebrates - visible signs (ha^{-1})	313.27 (5%)	7.14 (1%)	3.79 (3%)	78.97 (4%)	198.33 (1%)	3 711.67 (2%)

The average number of follicles per infructescence varied with species (Table 6.2). *B. grandis* had the largest number of follicles per infructescence, but had the lowest number of infructescences handled by Carnaby's cockatoos. *B. sessilis* recorded a mean of 1.2 follicles per infructescence however, the mean number of follicles per infructescence may actually be higher as a large proportion of follicles were collected in feeding residue trays and classified as one infructescence, as a consequence of the birds' method of seed extraction.

Table 6.2: Mean number of follicles per infructescence and number of follicles broken open by Carnaby's cockatoos for seed and larvae.

Species	Mean number of follicles (mean ± SE)		
	Total	Seed extracted	Larvae extracted
B. attenuata	11.6 ± 0.17	2.6 ± 0.08 (22%)	0.2 ± 0.02 (0.02%)
B. grandis	56.3 ± 12.33	29.1 ± 13.28 (52%)	0
B. ilicifolia	1.3 ± 0.05	0.6 ± 0.06 (43%)	0
B. menziesii	6.2 ± 0.15	2.5 ± 0.09 (40%)	0.1 ± 0.01 (0.01%)
B. prionotes	26.6 ± 0.64	7.0 ± 0.42 (26%)	<0.1 ± 0.01 (<0.01%)
B. sessilis	1.2 ± 0.05	0.7 ± 0.06 (56%)	0

Note: Larvae extracted from follicles only, larvae extracted from side of cone not included.

Less than 50% of banksia follicles investigated contained two firm seeds but this varied between species (Table 6.3). *B. attenuata* and *B. sessilis* on average recorded 45% of follicles with two firm seeds. *B. menziesii* recorded 39% of follicles containing two firm seeds and 31% with one firm seed. *B. prionotes* had 18% of follicles with two firm seeds and 12% with one firm seed. Conversely, *B. grandis* recorded no follicles with two firm seeds. Although *B. grandis* produced the largest number of follicles per infructescence, it is estimated that almost half would be barren. However, despite potentially only producing 32 seeds, *B. grandis* would still contain the highest number of seeds per infructescence for the *Banksia* species investigated.

Table 6.3: Number and percentage of banksia follicles that contained two, one or zero firm seeds.

Species	*n* follicles	Follicles with two firm seeds (%)	Follicles with one firm seed (%)	Follicles with zero firm seeds (%)	Average *n* seeds per follicle follicles (mean ± SE^{-1})
B. attenuata	916	45.7	35.7	18.6	1.27 ± 0.03
B. grandis	254	0	57.5	42.5	0.57 ± 0.03
B. ilicifolia	99	33.3	41.4	25.2	1.08 ± 0.08
B. menziesii	387	39.0	31.0	30.0	1.09 ± 0.04
B. prionotes	389	18.0	11.6	70.4	0.47 ± 0.04
B. sessilis	206	44.7	28.2	27.2	1.17 ± 0.06

Note: Follicles dispersed, insect damaged or manipulated by Carnaby's cockatoo were excluded from analysis.

B. sessilis had the smallest and lightest seed among the species investigated, averaging 0.007g dehusked (Table 6.4). *B. attenuata* seed was almost 11 times heavier than *B. sessilis*. Despite seed weight differences, seed energy content per gram was similar for all species with only 2.58 kJ g^{-1} difference between the highest, (*B. prionotes:* 22.90 kJ g^{-1}), and lowest (*B attenuata:* 20.32 kJ g^{-1}). *B. ilicifolia* seed energy yield was not tested due to low production rates during the sampling period and as such an average obtained from the other *Banksia species* was applied to this species.

The number of banksia infructescences required to meet the daily energy requirements of Carnaby's cockatoo was calculated using three different scenarios. These were: (1) all seeds were consumed per infructescence assuming two seeds per follicle using the mean number of follicles per infructescence; (2) all follicles opened by Carnaby's cockatoos contained two seeds using the mean number of follicles with seed extracted; and (3) all follicles opened by Carnaby's cockatoos contained the calculated average number of seeds per follicle using the mean number of follicles with seed extracted (Table 6.4). Three scenarios were investigated as tests on the number of firm seeds per follicle (Table 6.3) revealed that a large percentage contained fewer than two seeds. However, as this was only one sample in time, total assimilation of all follicles and seeds were included to show the difference in numbers of infructescences required, as previously reported by Cooper *et al.* 2002. Scenario 1 is the best case scenario where all follicles and seeds are available for consumption. Scenario 2 takes into account the number of follicles actually manipulated and assumes two seeds per follicle consumed by Carnaby's cockatoo, whereas Scenario 3 takes into account the number of follicles actually manipulated by Carnaby's cockatoo and the likely number of available seeds using seed numbers per follicle. Assuming that all follicles and seeds are available (Scenario 1), 21 *B. attenuata* infructescences are required each day to sustain a Carnaby's cockatoo. However, in the field not all seeds within follicles were available due to seed already being dehisced, eaten by invertebrates and naturally aborted. Based on the average number of follicles that had been broken open by Carnaby's cockatoo and the number of seeds extracted, between 93 and 147 *B. attenuata* infructescences would be required to meet daily energy requirements, using Scenarios 2 and 3 respectively. This estimate is at least five-fold greater than that of the best case scenario (Scenario 1). Given that *B. grandis* accounted for less than 1% of infructescence feeding activity by Carnaby's cockatoo this species is not likely to be an important food resource. *B. menziesii* on the other hand is an important food resource and the number of infructescences required to meet the birds' energy requirements ranges from 123 - 225 (Table 6.4). Fewer *B. prionotes* infructescences were required to meet the birds' daily energy requirements than *B. menziesii* using Scenario 2, however the addition of average number of seeds per follicle (Scenario 3) the number of *B. prionotes* infructescences required is double that of *B. menziesii*. *B. sessilis* recorded the greatest number of infructescences required for follicle extraction of seed at a range of 3 821 to 6 525 per day.

Table 6.4: Number of infructescences per day necessary to meet Carnaby's cockatoo calculated field metabolic requirements (FMR), based on the mean number of follicles per infructescence (two seeds per follicle); the mean number of follicles seed was extracted from (two seeds per follicle); and the mean number of follicles seed was extracted from, using seed productivity percentages. Carnaby's cockatoo estimated field metabolic rate 726 kJ d^{-1} (Cooper *et. al* 2002).

	Seed weight, energy, and number required to meet Carnaby's cockatoo field metabolic requirements			Scenario 1 (mean number of follicles per infructescence, two seeds per follicle)	Scenario 2 (mean number of follicles with seed extracted by Carnaby's cockatoo per infructescence assuming two seed per follicle)	Scenario 3 (mean number of follicles with seed extracted by Carnaby's cockatoo per infructescence using estimated number of firm seeds)
	Mean dry seed weight husked (g ± SE)	Seed energy content (kJ g^{-1})	*n* seeds to meet FMR (726 kJ d^{-1})	*n* infructescences d^{-1}	*n* infructescences d^{-1}	*n* infructescences d^{-1}
B. attenuata	0.075 ± 0.0036 (*n* = 20)	20.32*	476	21	**93**	**147**
B. grandis	0.045 ± 0.0023 (*n* = 20)	20.43*	790	7	**14**	**47**
B. ilicifolia	0.037 ± 0.0026 (*n* = 20)	21.36	919	342	**741**	**1 351**
B. menziesii	0.053 ± 0.0014 (*n* = 73)	22.27	615	50	**123**	**225**
B. prionotes	0.019 ± 0.0003 (*n* = 206)	22.91	1 668	31	**119**	**508**
B. sessilis	0.007 ± 0.0005 (*n* = 20)	20.90*	4 962	2 121	**3 821**	**6 525**

* Seed energy content Stock *et al.* (2013).
Note: *B. sessilis* husk was retained during seed energy investigations by Stock *et al.* (2013). Seed energy content for *B. ilicifolia* was estimated from the average of the other *Banksia* species (see methods).

Discussion

This study quantified the mean number of follicles and seeds per banksia infructescence and potential energetic reward as a food resource. This enabled the number of infructescences required to meet the daily field metabolic requirement for Carnaby's cockatoo to be calculated. By determining the energetic reward of banksia seed and the birds' metabolic requirements, this information can be used to assist in the management of the species to help ensure sufficient feeding habitat resources are protected.

The seed of Proteaceae species are characterised by large, winged seeds contained within serotinous follicles (Lamont & Groom 1998). Woody-fruited Proteaceous plants have nutrient-rich seeds, which are high in protein and low in fats (van Staden & Comins 1976; van Staden & Brown 1977; Kuo *et al.* 1982; Pate *et al.* 1985; Lamont & Groom 1998). Proteaceous plants often occur in habitats which are open and well-lit on highly infertile soils (Pate *et al.* 1985). As a consequence of growing in infertile soils proteaceous plants possess nutrient rich seeds which help increase seedling establishment and survival (Pate *et al.* 1985; Stock *et al.* 1990). A recent study by Stock *et al.* (2013) revealed that on average the protein yield of proteaceous seed was 62.1% compared to members from the Myrtaceae with 23.5% protein and Pinaceae family with 34.8% protein. In general proteaceous seeds are rich in total nitrogen, phosphorus and magnesium (Pate *et al.* 1985; Stock *et al.* 2013). On average *Banksia* and *Hakea* species have nitrogen levels much higher than other native (e.g. *Eucalyptus* spp.) and non-native (e.g. *Pinus* spp.) species (Stock *et al.* 2013).

Food selection based on quality is believed to be most important for black cockatoos during the breeding season (Johnstone & Kirkby 1999Chapman & Paton 2005, 2006;). Studies on the glossy black-cockatoo, *C. lathami halmaturinus*, suggest that breeding birds are more selective than non-breeding birds with regards to food sources (Chapman & Paton 2005, 2006). However, these studies focused exclusively on selection based on calorific energy gain. Sufficient uptake of protein and lipids may be important not only for the production of eggs (Ankney & Afton 1988) and development of growing nestlings (Valera *et al.* 2005), but also overall breeding success (Berry & Owen, 2010). Achieving a high level of body condition during the non-breeding season is likely to be just as important for breeding, since breeding success is dependent on body condition. Therefore selective feeding based on quality of food resource is likely to be important throughout the year (Berry & Owen, 2010).

The energy content of proteaceous plants is on average high, but is lower than other plant families such as Pinaceae (Stock *et al.* 2013). Using the energy yield of the eight proteaceous species analysed by Stock *et al.* (2013 together with *B. menziesii* and *B. prionotes* from this study, seed from Proteaceae species yield an average of 22.0 kJ g^{-1} compared with 25.8 kJ g^{-1} for *Pinus* species (Stock *et al.* 2013). Nonetheless, nutrient absorption and net energy gain of food resources after digestion by Carnaby's cockatoo have not been fully investigated. A study on the digestibility of Aleppo pine *P. halepensis* seed by the critically endangered Eyre Peninsula yellow-tailed black cockatoo *Calyptorhynchus funereus whitei,* a close relative of Carnaby's cockatoo, showed that metabolilsed energy was halved during digestion (Way 2006). When compared to proteaceous species, *P. halepensis* seeds were harder to digest, which reduced net energy gain (Way 2006). This may also be the case for Carnaby's cockatoos when comparing *Pinus* and *Banksia* seed digestibility and therefore the higher protein and more efficient digestibility of *Banksia* seed may be factors contributing to the selection of *Banksia* species by Carnaby's cockatoos.

The thermic effect of food is used to describe the increase in energy expenditure, by an organism, in response to the consumption and digestion of food (Jéquier & Schultz 1988). The composition of food consumed influences the thermic effect. The thermic effect of protein is 20 – 30% of energy consumed and for oil is around 3% (Acheson 1993). Therefore, the effective digestible energy of protein rich Proteaceae may be much lower than oil rich *Pinus* seed. The thermic effect of food in terms of daily energy expenditure is difficult to measure and replicate due to physiological factors, such as age, sex, physical fitness and genetic background (Tataranni *et al.* 1995). Avian thermic effects are unknown and it is expected that the number of infructescences required per day by Carnaby's cockatoos is an underestimate since the thermic effects have not been corrected for. However, it is important to note that the field metabolic rate of Carnaby's cockatoos, 726 kJ d^{-1} estimated by Cooper *et al.* (2002), was based on the basal metabolic rate of resting birds, using calculations by Williams *et al.* 1991 from measurements made on nesting female birds. Therefore the estimated field metabolic rate for Carnaby's cockatoo include metabolic costs associated with reproduction which may be higher than the average bird during non-breeding.

Energy expended in foraging for food and handling times also need to be considered. Plants that produce a large number of seeds and that are in close proximity to one another (e.g. plantations or thickets) may be more valuable as a food resource since less energy is expended to acquire the same amount of energy than for plants that produce fewer seeds spread over larger areas. Total energetic and nutrient yields per unit of time however are clearly not the only factors driving selection by Carnaby's

cockatoo, with seasonal availability of food resources shown to be an important factor, as not all food resources are available throughout the year (Chapter 4).

Banksia abundance and distribution varies significantly across the Swan coastal plain. *B. attenuata* and *B. menziesii* often co-exist in open woodlands with well-developed shrub understories in which they form the most common woodlands on the Swan coastal plain (Taylor & Hopper, 1988). In contrast *B. prionotes* and *B. sessilis* commonly occur in pure stands with high stem densities. However, patches of these species are often small and fragmented, surrounded by other vegetation types that are often dominated by *B. attenuata* and *B. menziesii*. *B. grandis* and *B. ilicifolia* are less common and occur scattered across the Swan coastal plain. Similarly, seed production also varies between *Banksia* species. In particular, seed production differs between resprouters and reseeders (refer to Chapters 2, 4 and 5), with level of seed production more important for reseeders as they rely exclusively on seed for post-fire recruitment (Lamont and Witkowski 1995; Richards and Lamont 1996). Seed production in resprouters is principally to facilitate species dispersal (Lamont and Witkowski 1995; Richards and Lamont 1996) and the ability to resprout after fire is negatively correlated with seed production (Keeley and Zedler 1978). Groom and Lamont (1996) showed that non resprouting proteaceous species produced more fruits per plant than resprouting proteaceous species. Although seed production is generally lower in resprouters, the seeds and fruits are larger (Lamont & Groom 1998). Despite *B. prionotes* and *B. sessilis* seed being smaller in size with fewer nutrients per seed, a vast amount of seed is produced which requires less effort and energy expenditure by Carnaby's cockatoos to acquire. This is the most likely reason for the number of infructescences handled and seed consumed per ha^{-1} by Carnaby's cockatoos being higher for *B. sessilis* and *B. prionotes.* On average *B. sessilis* produced 223 277 follicles per ha^{-1} compared to 6 348 follicles per ha^{-1} for *B. attenuata*. While consumption of *B. sessilis* and *B. prionotes* is higher, they are present at fewer sites than other *Banksia* species. Therefore the birds' utilise what is available, moving through the landscape feeding on a variety of species, with *B. attenuata* fed on frequently due to its widespread distribution and abundance across the plain.

Cooper *et al*. (2002) studied the energetic content of a variety of food resources for Carnaby's cockatoos and estimated a field metabolic rate of captive Carnaby's cockatoos of 726 kJ d^{-1} (Cooper *et al*. 2002). Cooper *et al*. (2002) calculated that 11 *B. attenuata* infructescences would be sufficient to meet a bird's daily field energy requirements. This estimate represented the minimum number of infructescences required daily, assuming two seeds per follicle and no metabolic cost of feeding. Using

the seed energy values of Stock *et al.* (2013), (which for *B. attenuata* was 1.7 kJ g^{-1} lower than those reported by Cooper *et al.* (2002)), the average number of follicles per infructescence established in this study and applying the same assumptions as Cooper *et al*. (2002), 21 infructescences would be required to meet the birds' daily energy needs. In contrast, if the average number of follicles opened by Carnaby's cockatoo per infructescence and the average number of seeds per follicle data are utilised, the number of infructescences required to meet the daily energy needs of Carnaby's cockatoos goes up to 93-147 per day for *B. attenuata*. Adjusting the calculation to allow for these additional factors provides a more realistic result and demonstrates that a pronounced increase in feeding effort is required by Carnaby's cockatoos.

While the estimates reported in this chapter provide a more realistic baseline for determining banksia food resource energy reward and daily requirements for Carnaby's cockatoos than that calculated by Cooper *et al.* 2002, there are several limitations associated with the birds' foraging behaviour and the study design. Feeding residues were removed from each quadrat bi-monthly which potentially removed a future food resource gained from ground foraging of fallen food items. Stock *et al.* (2013) reported ground foraging for more than half of the sample points recorded as part of their food plant investigations. Likewise, a proportion of follicles that were recorded as opened naturally may have had seed removed by Carnaby's cockatoos before the seed actually dehisced, which would impact on the daily number of infructescences required by Carnaby's cockatoos. The number of follicles per infructescence for *B. sessilis* may be higher as follicles collected in feeding residue trays were often counted as one infructescence due to the damage sustained during feeding. Therefore the number of infructescences required to meet daily energy requirements of the birds' may be lower for *B. sessilis*. It is also important to note that it cannot be assumed that closed follicles have 100% of seed resources available, as follicle seed counts showed that < 50% of the follicles contained two seeds. Witkowski *et al*. (1991) noted the loss of viable seeds is directly proportional to infructescence removal by cockatoos as they almost exclusively remove fertile infructescences. If this is the case then a proportion of the infructescences collected in this study for follicle productivity testing may have already been assessed or screened previously by the birds and rejected as a suitable food resource (e.g. knocked/tapped to determine viability through sound) which would mean that the calculations presented in this study over–estimate the number of fertile follicles and infructescences needed to meet the daily energy needs. Investigation of Carnaby's cockatoo feeding behaviour through cafeteria trials and field observations, and the examination of seed productivity of *Banksia* species, are required to resolve these issues.

Continued urbanisation, pine harvest plans and disturbance threats, including fire and disease, pose a real threat to Carnaby's cockatoo habitat and the birds' subsequent survival (DEC 2012). Loss of feeding habitat and fragmentation places increased pressure on available food resources. In Chapter 5 it was estimated that around 50% of banksia infructescences were utilised by Carnaby's cockatoos. However, this percentage is likely to increase with proposed plans to remove the Gnangara pine plantations north of Perth (Department of Water 2009). Pine plantations provide an important alternative food resource to banksia woodlands for Carnaby's cockatoos (Stock *et al.* 2013). The Gnangara pine plantation covered an area of 23 000 ha at its largest extent (Burrows *et al.* 2000). Since the establishment of pine plantations in the 1940s, Carnaby's cockatoos have successfully utilised this exotic seed food resource (Perry 1948, Saunders 1974, 1980, Finn *et al.* 2009), switching between pine and native resources at peak seed maturation periods (Stock *et al.* 2013). Research by Stock *et al.* (2013) suggests that Carnaby's cockatoos consume more than 85% of the annual cone production of pines in the Gnangara area. With a mean seed density of 158 025 pine seeds ha^{-1} (Stock *et al.* 2013), current banksia seed resources would be placed under significant pressure if the proposed complete removal of the Gnangara pines takes place without the re-establishment of an alternative food source on the former pine plantations or some other sites.

Effective conservation planning for Carnaby's cockatoo is dependent on improving the information on food resource usage and associated reward in order to characterise the value of habitat patches, guide land use planning and inform environmental impact assessments on the Swan coastal plain. These data can be used in conjunction with other research to assess areas for feeding habitat suitability for Carnaby's cockatoos.

Chapter 7: Banksia woodland habitat quality assessment for Carnaby's cockatoo on the Swan coastal plain

Introduction

Changes in environmental elements (e.g. location, vegetation distribution) or physical processes (e.g. fire, disease and other natural or human-made disturbances) can influence the distribution of plants or patterning of vegetation (Forman & Gordon 1981). In turn, these vegetation patterns influence the distribution of animals across the landscape in response to their niche requirements, including shelter and food availability. The distribution of individuals among habitats is often linked to their response to food resources and is very important as plans for the conservation of animal species are more often achieved through the management of their habitats (Morrison *et al.* 1998). Assessment of habitat quality (e.g. structure, function or productivity) helps to identify critical habitats, reveal overlap with anthropocentric impacts and guide management decisions regarding threatened species. Development of criteria for assessing habitat quality allows for the investigation of dynamic and varied situations in a relatively short timeframe with limited resources.

Local, state and national environmental agencies conduct bio-assessments to determine the condition of natural resources (Cao & Hawkins 2011) to help identify potential impacts of proposed planning (e.g. development) (Mörtberg *et al.* 2007). A key environmental factor for environmental agencies in Western Australia, such as the Environmental Protection Authority, when assessing environmental impact assessments is the protection of biological diversity (Environmental Protection Authority and Department of Environment and Conservation 2010). The role of Government in the assessment process is to ensure that there is adequate data of a high standard to inform environmental impact assessments (Environmental Protection Authority and Department of Environment and Conservation 2010). However, the environment is a multi-faceted system for which one rule does not apply to every situation or species. Understanding the specific biology and ecology of a species and the environment it inhabits is essential for uncovering patterns and factors which help highlight and or predict the potential importance of an area for that species.

Carnaby's cockatoo *Calyptorhynchus latirostris* is a threatened species, endemic to the south-west of Western Australia which is protected under State (Wildlife Conservation Act 1950) and Commonwealth (Environmental and Biodiversity Protection Act 1999) legislation. Carnaby's cockatoo is ranked as Endangered using the IUCN (2012) Red List Categories and Criteria, meeting Criterion A (1abc) since it has suffered a population decline of at least 50% over the past three generations or 45 years. The *Environmental Protection and Biodiversity Conservation* (EPBC) *Act 1999* provides a legal structure to protect and manage matters of national environmental significance of

which threatened species are listed (Environment Australia 1999). Under the EPBC Act framework referral guidelines for Carnaby's cockatoo have recently been developed to assist proponents in determining whether any proposed action (e.g. development) will have, or is likely to have, a significant impact on a species of concern (Commonwealth of Australia 2012). Habitat assessments include the extent, type and quality of the vegetation present, including the presence and extent of plants known to be used by Carnaby's cockatoos and any signs of use, including feeding residues. However, there are currently no formal criteria for assessing habitat quality for Carnaby's cockatoo, which take food resource availability into account. Before the interactions between landscape patterns and ecological processes can be understood landscape structure must be quantified in a logical and standard way (Turner 1989). Establishment of quantitative criteria through the use of vegetation characteristics allows direct comparisons to be made between different patches of vegetation, which should help to identify the significant environmental factors that relate to landscape patterns (Turner 1989), including food resource availability and foraging potential for Carnaby's cockatoo.

The objective of this study was to develop a protocol for surveying the quality of banksia woodland feeding habitat for Carnaby's cockatoo on the Swan coastal plain. The protocol establishes standard criteria for predicting infructescence availability by using banksia woodland characteristics to help identify habitat quality for Carnaby's cockatoos. The protocol was designed to include factors shown in Chapter 4 to have strong relationships with infructescence production such as stem density, canopy area and vegetation structure (e.g. height and girth), whilst allowing data to be collected in a cost-effective manner. A standard approach was developed to allow direct comparison to be made between habitats and species, facilitating fast and efficient identification of sites with good levels of food available for Carnaby's cockatoos. The application of this protocol will allow resource managers, planners and vegetation assessment officers to gain a broad ecological perspective and the ability to rank the importance of any given banksia woodland for Carnaby's cockatoos.

Method

Morphological and site characteristic models

Findings from Chapters 4, 5 and 6 on infructescence availability, consumption and seed reward were utilised to develop a habitat assessment protocol to assess the number of infructescences available in *B. attenuata, B. menziesii, B. prionotes* and *B. sessilis* woodlands. The correlation between the number of banksia infructescences available and numbers consumed by Carnaby's cockatoos was used in conjunction with energetic reward of banksia infructescences to determine a carrying capacity for the number of birds that could be supported ha^{-1} of banksia woodland. Multiple linear

regression models developed in Chapter 4 (Table 4.5) which highlighted the allometric relationships between plant morphological characteristics and the number of infructescences for each *Banksia* species were re-examined for their application in this assessment protocol. SPSS version 18 was used to run multiple linear regression models.

Generalised linear-nonlinear models (GLM) were used to investigate the relationship between the numbers of infructescences consumed by Carnaby's cockatoos in relation to several quadrat and site characteristics, these included:

- total number of infructescences available (quadrat),
- distance of site to the nearest night roost;
- number of night roosts within 12 km radius of the site;
- area (ha) of remnant vegetation within 12 km radius of the site;
- area (ha) of pine trees within 12 km radius of the site; and
- size of the site (ha).

A central point for each site was established and site characteristics quantified using spatial data and analysis software. The area of pine trees was established by combining the pine plantation polygons with pine point data (spatial layers: Pine_Plantations_Annual_Report, 2012, Forrest Products Commission and DEC_2009_Pine_Delimiting_Cli, 2012, Department of Agriculture and Food WA). For individual pine tree points, trees were assumed to have a canopy area of $100m^2$, which was averaged from measuring 10 pine trees. The area of remnant vegetation (Spatial layer: Remnant_Vegetation (Swan) 2012 Department of Agriculture and Food WA and DEC) and pine trees as well as the number of roosts within 12 km buffer around each site were measured and analysed according to buffered areas. The maximum buffer was set at 12 km as research by Saunders (1990) noted that Carnaby's cockatoos forage up to 12 km from roosts/nests within a day, which was also consistent with flock followings conducted by Shah (2006) who recorded foraging of the birds' up to 13 km. The number of roosts and distance from site was analysed using DEC spatial layer Carnaby's_ConfirmedAndUnconfirmed_Roosts2011_Points (2011).

Models were run in Statistica version 12.0 using GLM routine with a Poisson link function. Models were selected based on Akaike Information Criterion (AIC). Due to the sample size being < 40 times the number of parameters, AICc scores were calculated for each model (Anderson *et al.* 2001; Burnham and Anderson 2004). Akaike weights were calculated for all plausible models to express the strength of evidence for each model. To determine the relative strength of effect that each independent variable had on the dependant variable, the summed Akaike weight for each variable (Σw_{var}) was calculated. The effect strength of a variable can range from 0.00 to 1.00. When the best model or models contain a number of variables, all of these can have effect

strengths of 1.00, or all of them can have much lower effect strengths. Interpretation of Σw_{var} for a given variable depends of the effect strength of all other variables.

Habitat quality thresholds and habitat assessment

The upper and lower thresholds for the number of available infructescences ha^{-1} were established for *B. attenuata, B. menziesii, B. prionotes* and *B. sessilis* to identify the number of Carnaby's cockatoos that could be supported based on the birds' daily field energy requirements (726 kJ d^{-1}; Cooper *et al.* 2002). Thresholds were established using the linear relationships between infructescence availability and consumption (lower threshold), and the maximum potential infructescence consumption at a site which is the one to one line (upper threshold). Sites below the lower threshold showed high variability in usage, suggesting that Carnaby's cockatoos do not value these areas as much as other sites. These thresholds (actual consumption versus potential infructescences available) were generated to identify habitat quality for *Banksia* species and are those areas with high infructescence availability.

Due to the variability in the number of *Banksia* species present at each site, species composition was also analysed. As a consequence of mixed species woodlands, thresholds were required to assist with establishing a benchmark for determining the proportion of infructescences required to support Carnaby's cockatoos when more than one *Banksia* species was present.

Results

Morphological and site characteristic models

Multiple linear regression models developed in Chapter 4 (Table 4.5) were re-examined and variable combinations were analysed to reveal the most reliable model for each *Banksia* species whilst also being time efficient when considering application in the field. Canopy volume was removed from all analyses as it is a product of height and canopy area combined. Since the correlation coefficients generated for *B. attenuata* and *B. menziesii* models involving only one variable were in general low (< 23%), combinations were tested for application in this protocol. Multiple linear regression of all *B. attenuata* plant morphological variables accounted for 29% of the variability in the number of infructescences (Table 4.5). By removing the variables of age, number of reproductive stems and foliage height from the most predictive *B. attenuata* model (29%) the correlation coefficient was only slightly affected decreasing to 27% (Table 7.1). For *B. menziesii* the combination of all variables resulted in a correlation coefficient of 44% (Table 4.5). Removal of the variable age from *B. menziesii* models reduced the correlation coefficient to 42%. All the models tested for *B. sessilis* revealed significant ($P < 0.05$) relationships (Table 4.5). However, the variable foliage height revealed both a high correlation coefficient (85%) whilst also being relatively quick to measure in the field.

Table 7.1: Regression coefficients of the number of mature and Carnaby's cockatoo manipulated infructescences in relation to independent variables of plant morphological characteristics per quadrat (400m^2). Significance level $P < 0.05$.

Species	Variables	Coeff.	SE	F	d.f.	P	r^2
B. attenuata	Constant	10.30	9.67	8.68	3,71	0.00	0.27
	Height	-1.07	0.32				
	Girth	13.01	4.99				
	Canopy area	0.13	0.11				
B. menziesii	Constant	6.23	4.84	6.18	5,43	0.00	0.42
	Height	-0.96	0.33				
	Foliage height	1.22	0.47				
	Girth	10.60	5.40				
	Canopy area	0.16	0.15				
	No. of reproductive stems	-2.38	1.45				
B. sessilis	Constant	7 922.13	4 191.36	66.03	1,12	0.00	0.85
	Foliage height	86.60	10.66				

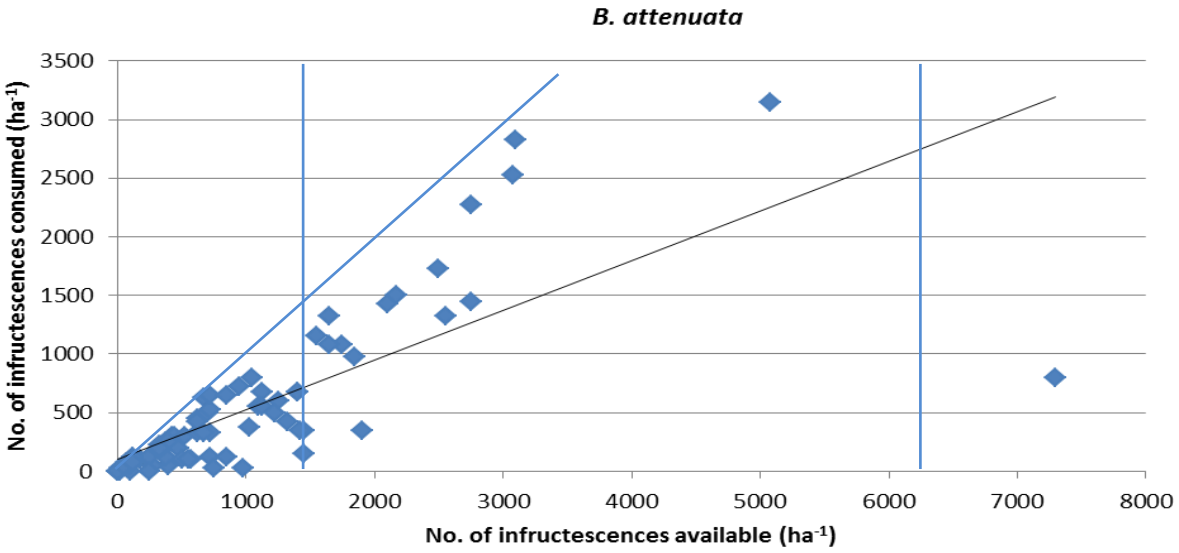
* Refer to Appendix 4 for all regression coefficients.

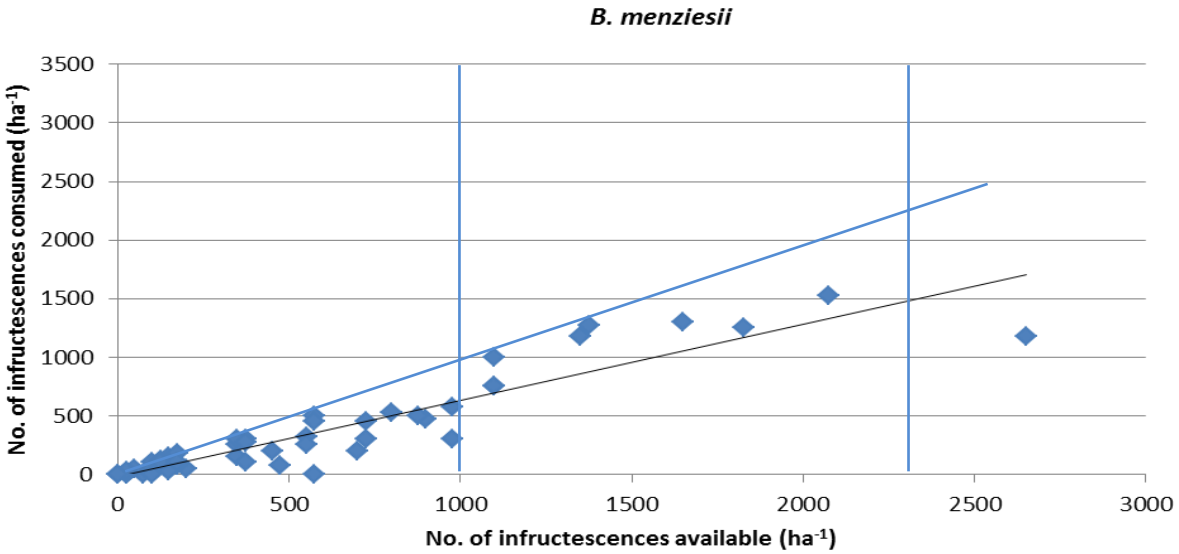
Table 7.2: Results of generalised linear modelling analyses on number of infructescences consumed by Carnaby's cockatoos (dependant variable) and site characteristics (independent variables). Models built using generalises linear-nonlinear routine with a Poisson link function.

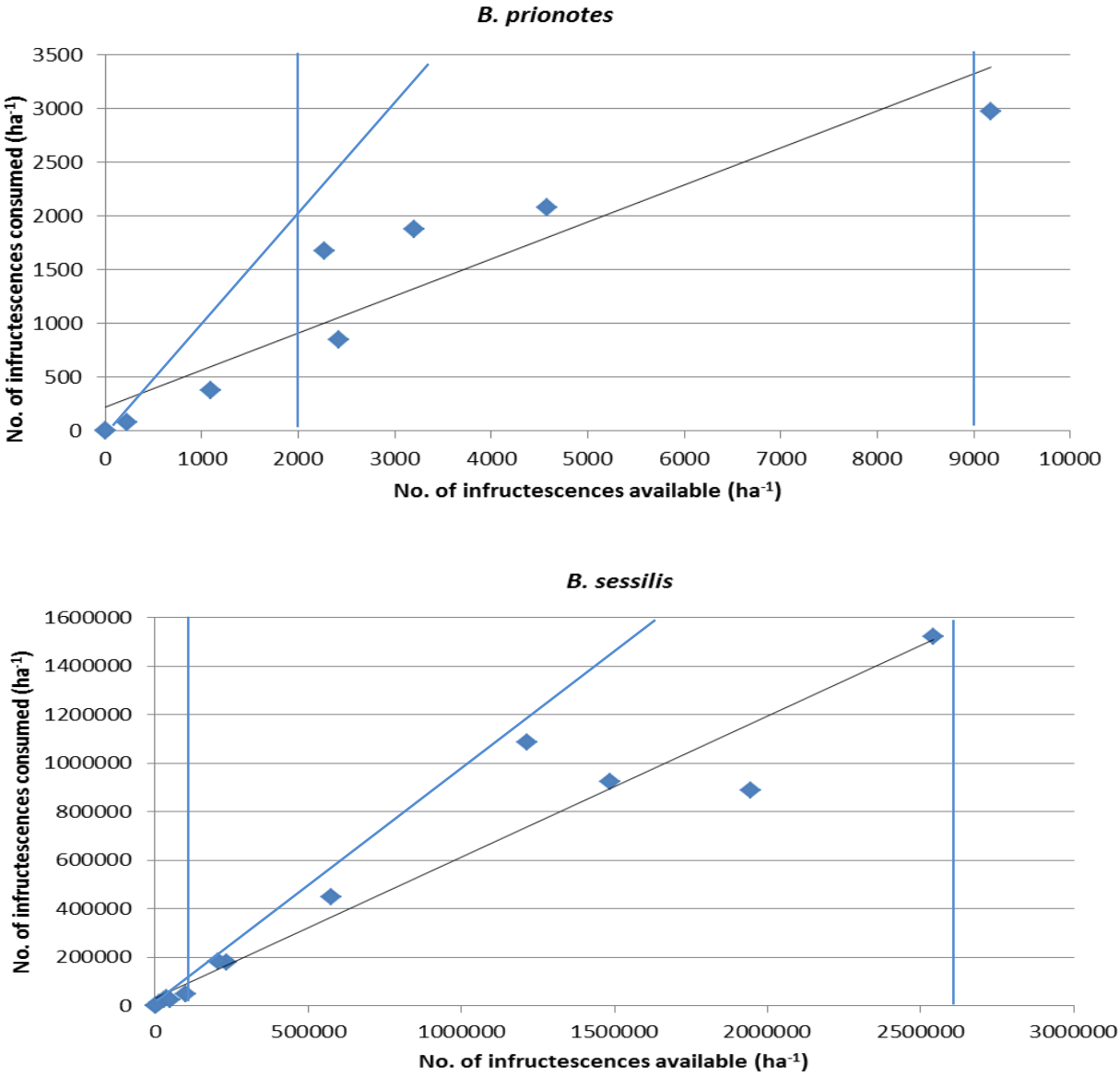
	N	Models	AICc	Δ_i	w_i
B. attenuata	75	Infructescence; Nearest roost; No. Roost; Pine; Size	1 094.93	0.00	0.68
	Σw_{var} = Infructescence 1 ; Nearest roost 1; No. roost 1; Remnant vegetation 0.25; Pine 1; Size 0.91				
B. menziesii	49	Infructescence; No. Roost; Pine; Size	401.19	0.00	0.39
		Infructescence; No. Roost; Remnant vegetation; Pine; Size	402.18	0.99	0.24
	Σw_{var} = Infructescence 1 ; Nearest roost 0.34; No. roost 1; Remnant vegetation 0.45; Pine 1; Size 0.81				
B. sessilis	14	Infructescence; Nearest roost; No. Roost; Remnant vegetation; Pine; Size	61 399.80	0.00	1.00
	Σw_{var} = Infructescence 1; Nearest roost 1; No. roost 1; Remnant vegetation 1; Pine 1; Size 1				

Shown are each candidate model for adjusted Akaike scores (AICc), difference in AICc with the top model (Δ_i) and Akaike weight (w_i), and for each variable the summed w_i over all models that included that variable (Σw_{var}). Only models with $\Delta_i < 2$ are shown. Variables: infructescence = total number of infructescences; nearest roost = distance to nearest roost; No. roost = number of roost within 12 km; remnant vegetation = area of remnant vegetation within 12 km; pine = area of pine within 12 km; size = size of site.

The GLM of the relationship between the numbers of infructescences consumed by Carnaby's cockatoos in relation to quadrat and site characteristics resulted in high effect strengths for a number of characteristics. For consumption of *B. attenuata* infructescences, the total number of infructescences available, distance of site to the nearest roost, number of roosts within 12 km radius of the site, area of pine trees within 12 km radius of the site and size of the site displayed high effect strengths. The effect strength for area of remnant vegetation within 12 km radius of the site was low for *B. attenuata* and *B. menziesii* consumption. The effect strength of distance of site to the nearest roost for number of *B. menziesii* infructescences consumed was also low. All characteristics investigated for *B. sessilis* resulted in high effect strengths.







Figures 7.1 - 7.4: Scatter plots of the linear relationship between the numbers of banksia infructescences consumed by Carnaby's cockatoos and the number available ha^{-1}. Thresholds are indicated by solid vertical lines. Note the scale change for *B. sessilis.*

Habitat quality thresholds and habitat assessment

The linear relationship between the numbers of infructescences consumed by Carnaby's cockatoos and the numbers available for each *Banksia* species were graphed (Figures 7.1 – 7.4) to determine the upper and lower thresholds of infructescence availability. The number of infructescences for *B. attenuata* ranged from 1 500 to 6 250 infructescences ha^{-1} (Table 7.3), which represented good quality habitat for Carnaby's cockatoos, supporting 10 – 43 birds d^{-1}. Good quality *B. prionotes* habitat however, could only support 4 – 18 birds ha^{-1} d^{-1}, despite requiring a larger number of

infructescences (2 000 – 16 000) than for *B. attenuata* (Table 7.3). Good quality *B. menziesii* habitat could support the lowest number of birds (5 – 10 birds ha^{-1} d^{-1}) with the number of infructescences required ranging from 1 000 to 2 300. The largest number of infructescences (100 000 – 2 600 000) was recorded in good quality *B. sessilis* habitat and accordingly could support the highest number of birds (15 – 399) ha^{-1} d^{-1} (Table 7.3).

Table 7.3: The number of Carnaby's cockatoos that can be supported ha^{-1} using the upper and lower thresholds of habitat quality as defined in Figures 7.1 – 7.4 using the mean number seeds consumed per infructescence for four *Banksia* species. Figures adjusted to standard energy requirement of Carnaby's cockatoo, 726 kJ d^{-1} (Cooper *et al.* 2002).

Thresholds		*B. attenuata*	*B. menziesii*	*B. prionotes*	*B. sessilis*
Lower	No. of birds	**10.2**	**4.4**	**3.9**	**15.3**
	Energy (kJ d^{-1})	7 405.2	3 194.4	2 831.4	11 126.4
	No. of infructescences	1 500.0	1 000.0	2 000.0	100 000.0
Upper	No. of birds	**42.5**	**10.2**	**17.7**	**398.5**
	Energy (kJ d^{-1})	30 855	7405	12 850	289 311
	No. of infructescences	6 250	2 300.0	9 000.0	2 600 000.0

Less than 18% of quadrats investigated contained single *Banksia* species stands (Figure 7.5), with the average being 2.2 ± 0.1 (mean ± SE) *Banksia* species per quadrat. To meet the daily energy requirements of one Carnaby's cockatoo in the presence of an evenly mixed *B. attenuata* and *B. menziesii* woodland (50:50), 74 and 113 infructescence respectively would be required (Table 7.4). Substituting *B. menziesii* with *B. sessilis* the number of infructescences required to meet the bird's metabolic requirements would be 3 263 infructescences. The combination of species which recorded the lowest number of infructescences required to meet the energy requirements of one bird was recorded for *B. attenuata* with 110 infructescences and *B. menziesii* with 56 infructescences (75:25 infructescences contributed respectively) (Table 7.4).

By using the lower thresholds (Table 7.3) and number of infructescences required to meet one bird's daily energy needs (Table 7.4), the number of infructescences required for habitat quality to be considered good can be established for a variety of mixed woodland habitats. For example, in an evenly mixed *B. attenuata* and *B. menziesii* woodland (50:50) Carnaby's cockatoos would require 735 *B. attenuata* infructescences

(support 5 birds) and 450 *B. menziesii* infructescences (support 2 birds) ha^{-1} to establish minimum standard for good quality habitat.

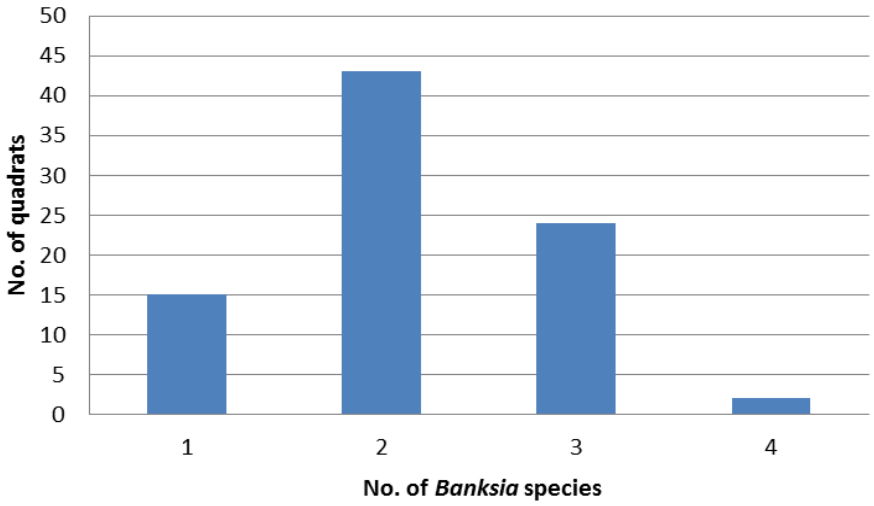


Figure 7.5: Number of *Banksia* species per quadrat.

Table 7.4: The number of infructescences ha^{-1} required to support one Carnaby's cockatoo (726 kJ d^{-1}) when dealing with more than one *Banksia* species per site**.** The mean number of seeds consumed by Carnaby's cockatoos per infructescence for each *Banksia* species was used to determine the number of infructescences required.

	No. of infructescences			
Banksia mix (%)	*B. attenuata*	*B. menziesii*	*B. prionotes*	*B. sessilis*
25	36.8	56.3	127.0	1 631.3
50	73.5	112.5	254.0	3 262.5
75	110.3	168.8	381.0	4 893.8
100	147.0	225.0	508.0	6 525.0

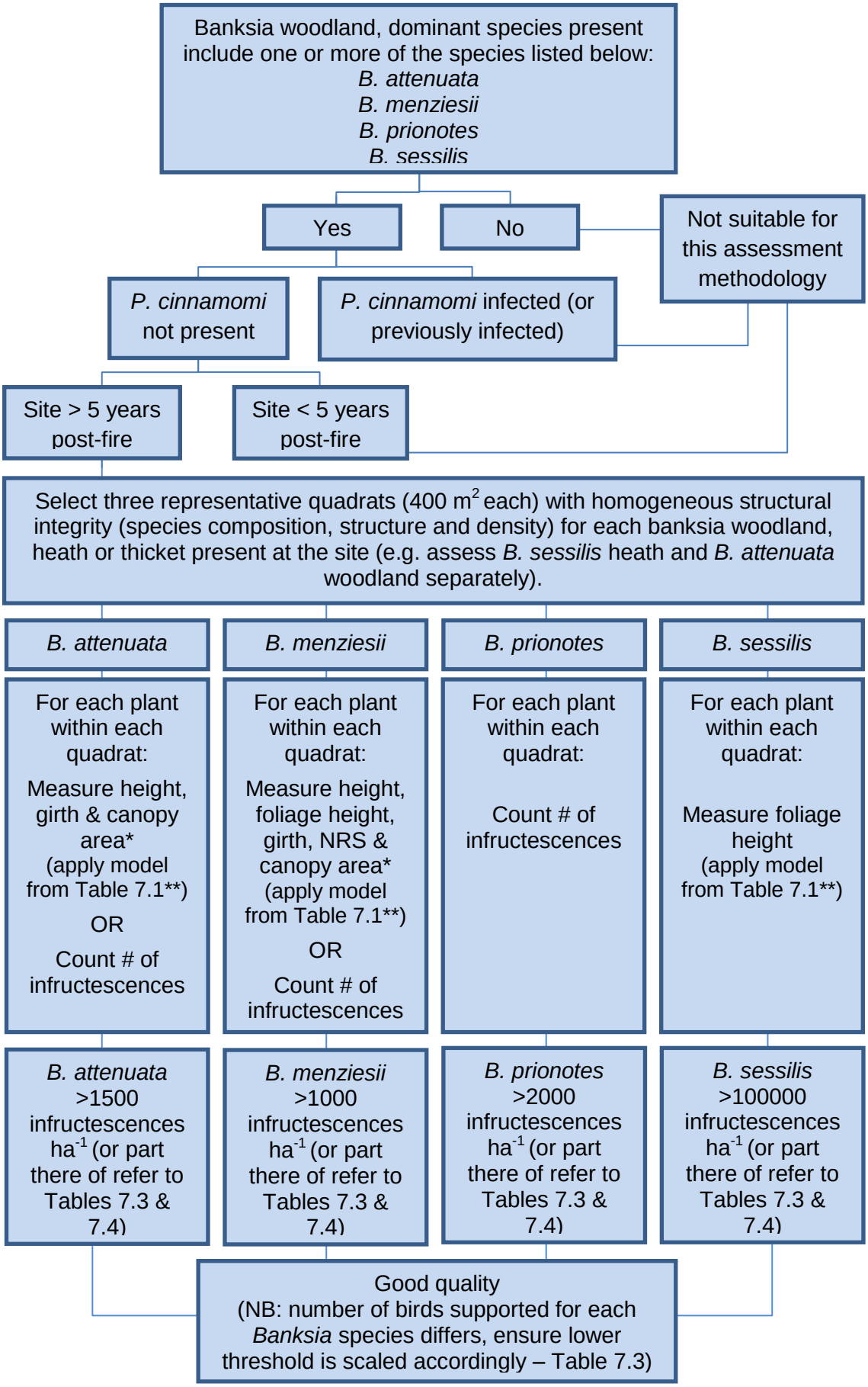
Discussion

The findings from this study provides a methodology for assessing the quality of banksia woodland feeding habitat for Carnaby's cockatoos (as set out in Figure 7.6). The development of a standard method for assessing food resource potential of *Banksia* species should assist and strengthen the decision-making processes regarding native vegetation management, whilst also being cost-effective. This study addressed gaps in knowledge and procedures for dealing with the assessment of the value of feeding habitat for Carnaby's cockatoo in the non-breeding season. The development of such an assessment protocol overcomes two major short-comings of the EPBC Act referral guidelines. Firstly, it provides defined benchmarks for assessing banksia woodland habitat quality by quantifying the number of infructescences and therefore potential energetic yield of a site for Carnaby's cockatoos. Secondly, the

protocol allows people with limited skills to carry out the assessments relatively quickly and easily, rather than needing to be carried out by a person experienced in surveying for black cockatoos. It is important to note that this chapter only provides methodologies for assessing banksia woodlands and further research into eucalyptus woodlands, pine plantations and other alternative food sources is urgently required.

The environment is a complex system and one management option or model is not applicable to every situation or species. It is important to understand why *Banksia* species models displayed varying results in comparison to one another. The main reason why the predictive models for *B. sessilis* were more reliable than those for *B. attenuata* and *B. menziesii* is most likely due to the plants reproductive biology. *B. sessilis* is a reseeder (Taylor & Hopper 1988; Lamont *et al*. 2007) which relies solely on regeneration through seed (Gill & Bradstock 1992). Therefore stands of *B. sessilis* are often more uniform in size, age and infructescence availability. In contrast, *B. attenuata* and *B. menziesii* are resprouters, often recovering from fire via vegetative epicormic buds which shoot post-fire, as well as by seed (Lamont & Markey 1995). Hence, *B. attenuata* and *B. menziesii* woodlands often consist of a variety of different aged individuals, which vary in size and infructescence availability. The biological differences between resprouters and obligate reseeders and their responses to fire, largely account for the differences presented between infructescence prediction models of the different *Banksia* species. In addition to reproductive biological differences these species are also morphologically different and therefore morphological characteristics identified as the most predictive factors for modeling also differed.

Canopy area, girth and height were strong predictors for the numbers of infructescences for *B. attenuata* when faced with reduced stand uniformity and increased variation, whereas the number of infructescences for *B. menziesii* was strongly associated with height, foliage height, girth, canopy area and number of reproductive stems. In comparison the number of infructescences for *B. sessilis* was strongly associated with all morphological characteristics measured which is largely due to the uniformity of plant structure between individuals. Despite the models for resprouting species being less reliable than for reseeders, predictive modeling is still a useful tool in estimating the potential food resource availability of an area. Caution needs to be applied to the application of the infructescence prediction models and further research is required to assess the effectiveness of applying the models and also to improve the predictive capacity and reliability of the models.



NRS = number of reproductive stems

***** Measure girth at 0.5 m above ground level. If there is more than one stem use methodology described on pp. 41 under *Plant Allometry*.

** Refer to Appendix 5 for habitat quality assessment equations for selected models.

Figure 7.6: Decision making tree diagram for habitat quality assessment.

Habitat Assessment Protocol

There are several things that need to be considered before undertaking a habitat assessment at a particular site. Quadrat selection needs to be carefully considered so as to ensure that representative patches of vegetation are selected with similar combinations of species, discernible boundaries between adjacent stands and similar structural integrity (e.g. spacing of plant species). Stands can be selected by evaluation prior to a site visit (e.g. delineated from aerial photos), however they may need to be adjusted or selected on site during reconnaissance to determine the extent, boundaries and location of other similar stands. Homogenous structural integrity is paramount when selecting sites to avoid skewed results. While this may be possible for *B. sessilis* stands, *B. attenuata* and *B. menziesii* woodlands are often highly variable even within the same site. For example, a few very large individuals may result in an increase in food resource availability for a particular quadrat, despite the overall quadrat displaying below average morphological characteristics. In contrast, a site with an above average number of reproductive stems may display a low infructescence density due to strong competitive interactions among the plants for resources such as nutrients, water and sunlight. Like structural integrity, *P. cinnamomi* needs to be considered when selecting quadrats. Disease resistance and or disease fronts can skew results, with the number of reproductive plants and available infructescences reduced by disease presence (refer to Chapter 4). *P. cinnamomi* infected areas, or areas that have previously been infected, should be avoided when selecting locations for assessment. Knowing these rules and applying them to a selection process will help avoid biased results and consequently inappropriate conservation management.

Fire is another element that needs to be considered when selecting quadrats or assessing a site. Banksia stands ≤ 5 years since last fire should not be assessed or assessed only with caution. *Banksia* species have developed two different methods of coping with fire. Some *Banksia* species resprout after fire from epicormic buds, which include *B. attenuata* and *B. menziesii* (Keeley 1986). Other species such as *B. prionotes* and *B. sessilis* are obligate seeders which rely on germination of seed for survival after fire (Gill & Bradstock 1992). In general both types of reproductive responses for *Banksia* species, and in particular those selected for this study, take around three to five years to first fruiting after fire (Lamont & van Leeuwen 1988; Witkowski *et al.* 1991; Lamont *et al.* 2007). However, maximum infructescence availability occurs anywhere between 5 and 15 years (refer to chapter 4) after fire. Given mature *B. attenuata* and to a lesser extent *B. menziesii* plants are not generally killed by fire, the impact of plant size becomes an issue when addressing the allometric relationship on infructescence availability. With no, or limited, infructescence availability but reasonable plant size sites ≤ 5 year post-fire may produce false readings. Although

potential food resource availability can be determined, results will most likely be an overestimation of current productivity, but will give a good indication of potential productivity (and value of the site to Carnaby's cockatoos in the future). This does not mean that sites ≤ 5 years post-fire are not valuable, but rather assessment should be conducted at a later date and or assessed with caution knowing that potential food resource availability will be delayed and interim management for Carnaby's cockatoo may need to be untaken.

To enable the consistent application of rules to assess habitat quality of potential Carnaby's cockatoo feeding areas a decision making flow diagram was developed (Figure 7.6). This flow diagram should assist proponents when undertaking habitat quality assessments of banksia woodlands on the Swan coastal plain. Recent fire sites (≤ 5 years post-fire) and *P. cinnamomi* sites are not suitable for assessment using these methods and selection of quadrats must be representative of the site. The flow diagram incorporates the lower habitat quality thresholds for the number of infructescences required for each *Banksia* species. Proposed model selection for infructescence assessments have been identified for each of the species. Given 82% of quadrats studied were mixed banksia woodlands, adjustments need to be made to incorporate information from Tables 7.3 and 7.4 to establish the proportion of infructescence of each *Banksia* species that contribute to habitat quality. Infructescence thresholds for each *Banksia* species were not scaled up to support an equal number of birds because good habitat quality varies for each of the *Banksia* species investigated.

For an assessment protocol to be successful it needs to incorporate cost effective and efficient assessment techniques to rapidly determine a baseline for conservation planning. Therefore, the model with the highest predictive capacity may not always be the most efficient model. Rather the predictive capacity and ease of undertaking an assessment needs to be carefully considered. Age as a predictive variable was removed from the decision making diagram as the contribution of this variable in determining the variability in number of infructescences for *B. attenuata* and *B. menziesii* was in general low and application in the field is very subjective and time consuming. Age was also removed from *B. sessilis* models, although it accounted for 70% of variability in the number of infructescences (Table 4.5), it is more difficult to age *B. sessilis* plants as age nodes are harder to distinguish. There were several models to choose from to determine the number of infructescences available for *B. sessilis*. The model that was selected for the assessment protocol for *B. sessilis* was foliage height, which accounted for 85% of variability. Although this was not the model with the highest predictive capacity, it is the most cost effective (e.g. time) while at the same time also being highly predictive compared to other model options. There was only a

7% difference in the coefficient of determination between this model and the most predictive option, which makes it the most cost effective since fewer measurements need to be made. In the case of *B. attenuata,* the model involving height, girth and canopy area is the most cost effective model to adopt. Only three factors need to be measured which reduces the time required to measure and record results. Given there is only a 2% difference between the most predictive model, which involves all variables, the model identified in the decision making diagram (Figure 7.6) would yield similar results. For *B. menziesii* additional plant morphological characteristics are retained as testing revealed that the removal of too many characteristics reduced the model's predictive capacity.

Due to the predictive capabilities of *B. attenuata* and *B.* menziesii infructescence models being poor, in comparison to *B. sessilis* models, it may be more efficient to count the number of infructescences directly rather than relying on allometric relationships. For *B. prionotes* this is the only option currently available due to the low number of sites sampled. It is important to note that, if infructescences are to be counted to determine food resource availability for Carnaby's cockatoos, then the time of year when the assessments are undertaken is paramount. *B. attenuata* assessments would need to occur between June and September and for *B. menziesii* and *B. prionotes* between December and January. Infructescences drying in the canopy and infructescences manipulated by Carnaby's' cockatoos will need to be counted, which despite taking more time to collect, will provide more reliable data than applying any of the models. Further investigation and research of banksia woodlands is strongly encouraged to refine these proposed assessment methods.

It is important to note that site variables, which include area of pine in close proximity, distance to nearest roost, number of roosts in close proximity and the size of the site, also influence the level of banksia infructescence consumption by Carnaby's cockatoos (Table 7.2). The habitat quality assessment protocol proposed in this study is based on data collected in a single year at a limited number of sites (21). Future use of this protocol will require testing of the methodologies and the potential addition of information on *Banksia* species composition, distribution, disturbance effects, and other environmental influences which will provide modifications to the existing protocol where necessary. While this protocol can be applied to obtain rapid information on a variety of *Banksia* species, the precision of each model is highly variable and the models are not good predictors of infructescence production for some of the species. To ensure the quality and applicability of the proposed allometric models, testing should be undertaken and models should be refined to enable their successful use in any assessment protocol.

Chapter 8 – Conclusions and recommendations

8.1 Conclusions and recommendations

Spatial and temporal use of feeding resources across the Swan coastal plain

The ability of Carnaby's cockatoos to travel long distances allows them to exploit food resources in response to spatial and temporal variation in production. This study identified Carnaby's cockatoo food preferences in proteaceous woodlands on the Swan coastal plain, which showed the birds to be flexible in their diet, consuming a variety of plant species and structures (infructescences, inflorescences and twigs), as well as invertebrates living in or on woody structures. Foraging signs by Carnaby's cockatoos were recorded from 24 species of plants in the study area of which six new plant species were identified (Chapter 3), increasing known food resource plants to 87 species. Over 60% of plant species manipulated by Carnaby's cockatoo were consumed for seeds contained in their fruiting structures. Carnaby's cockatoos readily change food sources, consuming resources across the Swan coastal plain. *Banksia* species were identified as the most widespread and heavily consumed genus with temporal variability in infructescence consumption throughout the year. This is most likely due to *Banksia* species possessing nutrient rich seeds (van Staden & Comins 1976; van Staden & Brown 1977; Kuo *et al.* 1982; Pate *et al.* 1985; Lamont & Groom 1998; Stock *et al.* 2013) and banksia woodlands forming the most dominant vegetation component on the Swan coastal plain (Heddle *et al.* 1980; Beard 1984; Gibson *et al.* 1994). *B. attenuata, B. menziesii, B. prionotes* and *B. sessilis* were the *Banksia* species most frequently consumed by Carnaby's cockatoos within the study area. There was a clear drop in infructescence consumption between September and November and an increase observed between December and February, which is consistent with published observations of migration breeding behaviour of Carnaby's cockatoo.

Foraging behaviour

Optimal foraging theory suggests that organisms forage in such a way as to select foods that convey maximum net energy intake per unit feeding time (Lack 1954; MacArthur & Pianka 1966). The foraging behaviour of Carnaby's cockatoos appeared to follow optimal foraging theory, with the pattern of food resource consumption a consequence of the proximity and availability of seeds. Areas with a high density of food resources minimise the number of movements made by the birds between plants, which consequently reduces energy expenditure for foraging and feeding. This was evident with a noticeable decline in banksia use recorded in April (Chapter 5), which coincided with peak Maritime Pine *Pinus pinaster* cone consumption (Stock *et al.*

2013). Although pine plantations in the study area covered a territory eight times smaller than potential remnant vegetation feeding resources, pine plantations occurred in monocultures and produced a large number and density of cones and seed (Stock *et al.* 2013). Increased feeding intensity by Carnaby's cockatoo was also observed where *B. sessilis* occurred in stands with high stem densities. Fluctuations in feeding intensity between different food resources by Carnaby's cockatoo suggests that plants which produce a large number of seeds and which are in close proximity to one another (e.g. plantations or thickets), may be more valuable as food resources since net energy intake per unit feeding time is maximized compared to plants that produce fewer seeds spread over larger areas (e.g. *B. attenuata* and *B. menziesii* woodlands). However, this conclusion needs to be tempered by the fact that Carnaby's cockatoos fed at all 21 sites investigated in this study, suggesting that feeding habitat is already in critical supply.

Seed reward and availability

Energetic content of banksia seeds (g^{-1}) was very similar between the species investigated in this study and previous research conducted by Stock *et al.* (2013), with only a 2.6 kJ g^{-1} difference recorded. Given that the seed energetics amongst *Banksia* species was similar, the focus was turned to seed weight and availability as determining factors for the number of seeds/infructescences required to meet field metabolic requirements of Carnaby's cockatoo. Seed weight varied between species, with some species weighing ten times more than others (e.g. *B. attenuata* seed 0.075 g versus *B. sessilis* seed 0.007 g). However, despite smaller seeding *Banksia* species (e.g. *B. prionotes* and *B. sessilis*) delivering less energy per seed, these species produced a larger number of seeds: up to 35 times greater the number of follicles per hectare than species with heavier seeds (e.g. *B. attenuata* and *B. menziesii*). This allowed for a greater number of birds to be supported over the same area despite requiring a greater number of seeds and infructescences to be handled (e.g. Carnaby's cockatoo require 93 – 147 *B. attenuata* infructescences d^{-1} versus 3 821 – 6 525 *B. sessilis* infructescences d^{-1}).

The smaller seeding *Banksia* species investigated in this study have restricted distributions, with stands often small in size despite high stem densities (m^{-2}) and seed yield, and were often surrounded by species such as *B. attenuata* which are common and widespread across the Swan coastal plain. The confined distribution of smaller seeding *Banksia* species in this study is likely to be a direct result of the species reproductive biology as they are obligate reseeders which rely solely on seed to regenerate. Obligate reseeders are more vulnerable to stochastic events since many of

them take 3-7 years to become reproductive after a disturbance event such as fire (Witkowski *et al.* 1991; Enright *et al.* 1996; Lamont & Markey 1995). Appropriate intervals between fires are also needed to retain obligate reseeders in the system, since these species have limited lifespans (30-50 years) (Gill & McMahon 1986; Witkowski *et al.* 1991; Burgman and Lamont 1992). Therefore although small seeding banksias produce large quantities of seed, availability may be limited, reducing species' distribution and contribution as a food resource for Carnaby's cockatoo.

Consumption rates

Strong linear relationships between banksia infructescence availability and infructescence consumption by Carnaby's cockatoos were shown for all *Banksia* species (Chapter 5) across the study area. Despite habitat heterogeneity, such as number of reproductive stems m^{-2}, species composition, post-fire age and presence of *P. cinnamomi*, consumption levels were consistently proportional with infructescence availability suggesting Carnaby's cockatoos were exploiting all available resources across the Swan coastal plain. Carnaby's cockatoos showed dietary switching between *Banksia* species and other food resources (e.g. *P. pinaster*), which often coincided with the period of peak infructescence/cone maturation.

The high level of infructescence consumption raises concerns about current food resource availability and population sustainability for Carnaby's cockatoos. The environment which Carnaby's cockatoo inhabits is constantly changing and the ability to adjust foraging behaviour is essential for maximising fitness (e.g. breeding success is dependent on the level of body condition acquired during the non-breeding season). Since 1900 the human population of the greater Perth area has appropriated significant resources, from ground water, to land for urban development and market gardening (Weller 2009). Continued urbanisation, pine harvest plans and disturbance threats, including fire and disease, pose a real threat to Carnaby's cockatoo habitat and the birds' subsequent survival (DEC 2012). The loss of feeding habitat will place increased pressure on remaining food resources. The proposed plan to remove the Gnangara pine plantations north of Perth (DOW 2009), which have been identified as important foraging grounds for Carnaby's cockatoo (Stock *et al.* 2013), will increase pressure on banksia seed resources, significantly affecting the carrying capacity of Carnaby's cockatoos in banksia woodlands.

Management requirements

As a consequence of the biological differences between *Banksia* species and the response of Carnaby's cockatoo to food resource availability, consideration needs to be given to managing a variety of habitats of varying species composition, structure, time since last fire and distribution across the Swan coastal plain. For example, *B. sessilis* is an important food resource for Carnaby's cockatoo but its restricted distribution, biological response to fire and inability to provide a stable food resource all year round make it an unreliable food resource on its own. However, in combination with *B. attenuata*, the abovementioned limitations are overcome as *B. attenuata* woodlands are common across the Swan Coastal Plain, have the ability to resprout following fire and provide food resources at contrasting times to *B. sessilis*. The conservation of a variety of banksia foraging habitats for Carnaby's cockatoo in different locations is necessary to ensure feeding resources are available throughout the year to protect against the impact of threatening processes such as too frequent fire and *P. cinnamomi*.

Factors which help predict food resource availability

To ensure sufficient food resources are available it was essential to identify the factors which help to predict food resource availability and habitat quality for Carnaby's cockatoos (Chapter 4). This study showed that time since last fire and presence of *P. cinnamomi* influenced infructescence availability, while soil type had no effect. As shown in Chapter 4, food resource availability is negatively, and most likely permanently, impacted by the presence of *P. cinnamomi*. Although food may still be available in the presence of *P. cinnamomi*, the long term availability of food resource plants susceptible to *P. cinnamomi,* which include *Banksia* species*,* is ultimately limited as continued spread of the disease will most likely kill any persisting plants and *P. cinnamomi* sensitive species cannot then be used to revegetate affected sites or establish new habitat. Post-fire age has a considerable effect on banksia infructescence availability, with peak infructescence availability occurring between 6-15 years of age for *B. sessilis*, 11-15 years for *B. menziesii* and > 16 years for *B. attenuata* post-fire (Chapter 4). Stands ≤ 5 years of age post-fire were the least productive for *B. attenuata, B. menziesii* and *B. sessilis*. Unlike the presence of *P. cinnamomi,* reduced infructescence availability in recent fire sites (≤ 5 years post-fire) is likely to only be temporary and once the plants have recovered from fire they will again be important feeding areas.

Analysis and modeling of plant allometric relationships between infructescence availability and plant morphological characteristics identified several variables that assist in predicting banksia infructescence numbers (Chapter 4). Different morphological characteristics were identified as the most predictive factors for modeling for each *Banksia* species, with canopy volume, plant height, girth and foliage height variously identified as highly predictive variables.

Habitat quality assessment

The overarching aim of this study was to establish quantitative criteria for assessing banksia woodland habitat quality for Carnaby's cockatoo for effective integration of biodiversity issues into planning and impact assessment processes (Objective 5). The integration of banksia infructescence availability (Chapter 4), knowledge of the birds' foraging behaviour (Chapter 5) and the seed energy yield (Chapter 6) of *Banksia* species helped in the development of a habitat assessment protocol. Development of a standard approach as outlined in Chapter 7 enables direct comparison to be made between banksia sites and assessment of the relative quality of each site is facilitated through the use of the assessment protocol.

Listed as a threatened species under State and Commonwealth legislation any proposed action (e.g. development) that will have, or is likely to have, a significant impact on Carnaby's cockatoo must have an environmental impact assessment conducted. Current environmental impact assessments do not provide quantitative predictions for conserving habitat for Carnaby's cockatoos which is a major constraint for proposed developments and conservation management. To overcome the shortfalls of current feeding habitat assessment methodologies, the habitat assessment protocol proposed in this thesis provides a starting point for assessment of feeding habitat. It is important to note this protocol is based on one year's field data from 21 sites and its adoption will require testing to ensure the number of infructescences can be successfully estimated across a wide range of environmental and climatic conditions.

Areas being considered for protection or addition to any reserve system through the use of this habitat assessment protocol also need to be assessed for *P. cinnamomi* presence and risk of its introduction and/or spread. Additionally, when considering the implications of fire as a selection variable in conservation management, managers need to be mindful that each *Banksia* species is different, requiring a specific set of fire regimes for sustainable infructescence production (Chapter 4). Frequent fire and long absence of fire may be just as undesirable for species like *B. sessilis,* leading to a reduction in infructescence availability. Managed, small scale, mosaic burns in

conservation areas need to be carefully planned in accordance with each specie's biology as well as fire risk to sites from both natural and anthropocentric causes, in order to safeguard food resources for Carnaby's cockatoo.

Project outcome

The main aims of this thesis were successfully addressed and have increased the understanding of Carnaby's cockatoo feeding preferences and foraging behaviour in the banksia woodlands of the Swan coastal plain. The results have revealed patterns and factors which help predict the potential habitat importance of an area for Carnaby's cockatoos. It is hoped that the data presented in this thesis will be used in context with the State environmental assessment processes to evaluate banksia woodland habitat quality for non-breeding Carnaby's cockatoos on the Swan coastal plain to achieve sustainable development and preservation of this iconic Western Australian species.

References

Abbott I. (1985) Rate of growth of *Banksia grandis* Willd. (Proteaceae) in Western Australian forest. *Australian Journal of Botany* **33**, 381–391.

Acheson K.J. (1993) Influence of autonomic nervous system on nutrient-induced thermogenesis in humans. *Nutrition* **9**, 373-380.

Anderson D.R., Link, W.A., Johnson D.H. & Burnham K. (2001) Suggestions for presenting the results of data analyses. *Journal of Wildlife Management* **65**, 373-378.

Ankney C.D. & Afton A.D. (1988) Bioenergetics of breeding northern shovelers: Diet, nutrient reserves, clutch size and incubation. *The Condor* **90**, 459-472.

Banko P.C, Oboyski P.T, Slotterback J.W., Dougill S.J., Goltz D.M., Johnson L., Laut M.E., & Murray T.C. (2002) Availability of food resources, distribution of invasive species, and conservation of a Hawaiian bird along a gradient of elevation. *Journal of Biogeography* **29**, 789–808.

Beard J.S. (1980) *Sheet 7, Swan, Vegetation Survey of Western Australia 1:1,000,000 Series*. University of Western Australia Press, Nedlands.

Beard J.S. (1984) Biogeography of the Kwongan. In *Kwongan: plant life of the sand plain: biology of a south-west Australian shrubland ecosystem* (eds. J.S. Pate & J. S. Beard), pp. 1–26. University of Western Australia Press, Nedlands, Western Australia.

Beard J.S. (1989) Definition and location of the banksia woodlands. *Journal of the Royal Society of Western Australia* **71**, 85-86.

Bell D. T. & Stephens L. J. (1984) Seasonality and phenology of Kwongan species. In *Kwongan: plant life of the sand plain: biology of a south-west Australian shrubland ecosystem* (eds. J.S. Pate & J. S. Beard), pp. 205-226. University of Western Australia Press, Nedlands, Western Australia.

Berry P. F. & Owen M. (2010) Additional counts and records of flock composition of Carnaby's cockatoo (*Calyptorhynchus latirostris*) at two overnight roosting sites in metropolitan Perth. *The Western Australian Naturalist* **27**, 27-38.

Bettenay E., McArthur W.M. & Hingston, F.J. (1960) *The soil associations of part of the Swan Coastal Plain, Western Australia*. CSIRO Division of Soils, Soils and Land Use Series No. 35.

Bureau of Meteorology (2012a) Perth metropolitan mean rainfall. Australian Government, Bureau of Meteorology. Retrieved June 2012 from the Australian Government, Bureau of Meteorology website: http://www.bom.gov.au/jsp/ncc/cdio/cvg/av?p_stn_num=009225&p_prim_element_index=18&p_display_type=statGraph&period_of_avg=ALL&normals_years=allYearOfData&static

Bureau of Meteorology (2012b) Perth 2010 annual climate summary. Australian Government, Bureau of Meteorology. Retrieved June 2012 from the Australian Government, Bureau of Meteorology website: http://www.bom.gov.au/climate/current//annual/wa/archive/2010.perth.shtml

Bureau of Meteorology (2012c) Perth 2011 annual climate summary. Australian Government, Bureau of Meteorology. Retrieved June 2012 from the Australian Government, Bureau of Meteorology website: http://www.bom.gov.au/climate/current//annual/wa/archive/2011.perth.shtml

Burgman M.A. & Lamont B.B. (1992) A stochastic model for the viability of *Banksia cuneata* populations: environmental, demographic and genetic effects. *Journal of Applied Ecology* **29**, 719-727.

Burnham Q., Barrett G., Blythman M. & Scott, R. (2010) *Carnaby's Cockatoo (*Calyptorhynchus latirostris*) identification of nocturnal roost sites and the 2010 Great Cocky Count.* Birds Australia Western Australia and the Western Australia Department of Environment and Conservation, WA.

Burnham K. P & Anderson D. R. (2004) Multimodel inference: understanding AIC and BIC in model selection. *Sociological Methods and Research* **33,** 261–304.

Burrows N.D. (2008) Linking fire ecology and fire management in south-west Australian forest landscapes. *Forest Ecology and Management* **255**, 2394–2406.

Burrows N., Ward B. & Robinson A. (2000) Behaviour and some impacts of a large wildfire in the Gnangara maritime pine (*Pinus pinaster*) plantation, Western Australia. *CALM Science* **3**, 251–260.

CALM (2001) *Phytophthora cinnamomi and the diseases caused by it. Volume 2: interpreters guidelines for detection, diagnosis and mapping*. Department of Conservation and Land Management, Western Australia, Perth.

Canham C.A., Froend R.H. & Stock W.D. (2008) Water stress vulnerability of four *Banksia* species in contrasting ecohydrological habitats on the Gnangara Mound, Western Australia. *Plant, Cell & Environment* **32**, 64-72.

Cao Y. & Hawkins C.P. (2011) The comparability of bioassessments: a review of conceptual and methodological issues. *Journal of North American Benthological Society* **30**, 680-701.

Carpenter F.L. (1978) Hooks for mammal pollination. *Oecologia* **35**, 123-132.

Chapman T.F. & Paton D.C. (2005) The glossy black-cockatoo (*Calyptorhynchus lathami halmaturinus*) spends little time and energy foraging on Kangaroo Island, South Australia. *Australian Journal of Zoology, **53***, 177-183.

Chapman T.F & Paton D.C. (2006) Aspects of Drooping Sheoaks (*Allocasuarina verticillata*) that influence Glossy Black-Cockatoo (*Calyptorhynchus lathami halmaturinus*) foraging on Kangaroo Island. *Emu* **106**, 163–168.

Clifford H.T. & Drake W.E. (1981) Pollination and dispersal in eastern Australian heathlands. In: *Ecosystems of the World. Heathlands and Related Shrublands. Analytical Studies* (R.L. Specht Ed.), Elsevier Scientific Publishing Co, Amsterdam, pp. 39-49.

Collins K., Collins C. & George A.S. (2008) *Banksias.* Bloomings Books, Melbourne, Australia.

Collins D.A, Della-Marta P.M., Plummer N. & Trewin B.C. (2000) Trends in annual frequencies of extreme temperatures in Australia. *Australian Meteorological Magazine* **49**, 272 -292.

Commonwealth of Australia (2012) EPBC Act referral guidelines for three threatened black cockatoo species: Carnaby's cockatoo (endangered) *Calyptorhynchus latirostris,* Baudin's cockatoo (vulnerable) *Calyptorhynchus baudinii,* Forest red-tailed black cockatoo (vulnerable) *Calyptorhynchus banksii naso. Australian Government,* Department of Sustainability, Environment, Water, Populations and Communities, Canberra.

Cooper C. E., Withers P.C., Mawson P.R., Bradshaw S.D., Prince J. and Robertson H. (2002) Metabolic ecology of cockatoos in the south-west of Western Australia. *Australian Journal of Zoology* **50**, 67-76.

Cowling R.M. & Lamont B.B. (1987) Post-fire recruitment of four co-occurring *Banksia* species. *Journal of Ecology* **24**, 645-658.

Cowling R.M., Lamont B.B. & Pierce S.M. (1987) Seed bank dynamics of four co-occurring Banksia species. *Journal of Ecology* **75**, 215-221.

Dawson R., Saunders D.A. and Mawson P. (2011) The vulnerable and the endangered: Carpet python predation on a breeding female Carnaby's black cockatoo. *Australian Zoologist* **35**, 678-680.

Department of Environment and Conservation (DEC) (2012) Carnaby's cockatoo (*Calyptorhynchus latirostris*) Recovery Plan. Department of Environment and Conservation. Perth Western Australia.

Department of Water (2009) Gnangara Sustainability Strategy: draft for public comment. Gnangara Coordinating Committee. Retrieved August 2012 from the Department of Water, Western Australia web site: http://www.water.wa.gov.au/sites/gss/Content/Projects/GSS_DraftStrategy.pdf

Earle K.E. & Clarke N.R. (1991) The nutrition of the budgerigar *Melopsittacus undulatus. Journal of Nutritio*n **121**, 186-192.

Enright N.J. & Lamont B.B. (1989) Seed banks, fire season, safe sites and seedling recruitment in five co-occurring Banksia species. *Journal of Ecology* **77,** 1111-1122.

Enright N.J., Lamont B.B. & Marsula R. (1996) Canopy seed bank dynamics and optimum fire regime for the highly serotinous shrub, *Banksia hookeriana. Journal of Ecology* **84**, 9-17.

Environment Australia (1999). *Environment Protection and Biodiversity Conservation Act.* Department of the Environment and Heritage, Canberra.

Environmental Protection Authority and Department of Environment and Conservation (2010) *Technical Guide - Terrestrial Vertebrate Fauna Surveys for Environmental Impact Assessment* (eds. B.M. Hyder, J. Dell and M.A Cowan). Perth, Western Australia.

Finn H., Stock W. & Valentine L.E. (2009) *Pines and the ecology of Carnaby's Black-Cockatoos* (Calyptorhynchus latirostris) *in the Gnangara Sustainability* Strategy Area. Report to the Forest Products Commission. Centre for Ecosystem Management, Edith Cowan University and the Department of Environment and Conservation.

Fitzpatrick R.W. (2008) Soils and Natural Resource Management. In: *Regolith Science.* (Eds. KM Scott and CF Pain). pp. 307-339 (colour plates: pp 172-174). CSIRO Publishing (Australia) and Springer.

Forman R. T. T. & Godron M. (1981) Patches and structural components for a landscape ecology. *Bioscience* **31**, 733-740.

Garnett S.T., Szabo J.K. & Dutson G. (2011) *The Action Plan for Australian Birds 2010.* CSIRO Publishing, Collingwood.

Gentilli J. & Fairbridge R.W. (1951) *The Physiographic Regions of Australia*. Notes to accompany a Geomorphological Map of Australia by J. Gentilli, University of Western Australia, Nedlands, WA.

George A.S. (1981) The Genus *Banksia* L.f. (Proteaceae). *Nuytsia* **3**, 239-473.

George A.S. (1984) *The Banksia Book*. Kangaroo Press Pty Ltd, Sydney.

Gibson N., Keighery B.J., Keighery G.J., Burbidge A.H. & Lyons M.N. (1994) *A Floristic Survey of the Southern Swan Coastal Plain*. Unpublished Report for the Australian Heritage Commission prepared by Department of Conservation and Land Management and the Conservation Council of Western Australia (Inc.), Perth.

Gill A.M. & Bradstock R.A. (1992) A national register for the fire response of plant species. *Cunninghamia* **2**, 653–660.

Gill A.M. & McMahon A. (1986) A post-fire chronosequence of cone, follicle and seed production in *Banksia ornata*. *Australian Journal of Botany* **34**, 425-433.

Government of Western Australia (2000) *Bush Forever. Volume 2: Directory of bush forever sites*. Department of Environment Protection, Perth, WA.

Groom C. (2010) *Plants for Carnaby's Search Tool.* Department of Environment and Conservation (DEC). Retrieved January 2012, from DEC website: http://www.dec.wa.gov.au/content/view/5983/2006/

Groom P. K. & Lamont B. B. (1996). Reproductive ecology of non-sprouting and resprouting species of *Hakea* (Proteaceae) in southwestern Australia. In '*Gondwanan Heritage: Past, Present and Future of the Western Australian Biota'.* (Eds S. D. Hopper, M. Harvey, J. Chappill & A. S. George.) pp. 239-248. Surrey Beatty, Chipping Norton.

Hanley M.E. & Lamont B.B. (2001). Herbivory, serotiny and seedling defence in Western Australia Proteaceae. *Oecologia* **126**, 409–17.

Heddle E.M., Loneragan O.W. & Havel J.J. (1980). Vegetation of the Darling System. In: *Atlas of Natural Resources, Darling System, Western Australia*. Department of Conservation and Environment. Government of Western Australia.

Heinrich B. & Collins S. L. (1983). Caterpillar leaf damage, and the game of hide-and-seek with birds. *Ecology **64**,* 592-602.

Higgins P.J. (1999) *Handbook of Australian, New Zealand and Antarctic Birds Volume 4: Parrots to Dollarbird.* Oxford University Press, Melbourne.

Hill T.C.J, Tippett J.T. & Shearer B.L. (1994) Invasion of Bassendean Dune banksia woodland by *Phytophthora cinnamomi*. *Australian Journal of Botany* **42**, 725-738.

Hutto R.L. (1990) Measuring the availability of food resources. *Avian Biology* **13**, 20-28.

IUCN. (2012) *Guidelines for application of IUCN Red List Criteria at regional and national levels: Version 4.0.* IUCN, Gland, Switzerland.

Jéquier E. & Schultz Y. (1988) Energy expenditure in obesity and diabetes. *Diabetes Metabolism Research and Review* **4**, 583–593.

Johnson M.D. & Sherry T.W. (2001) Effects of food availability on the distribution of migratory warblers among habitats in Jamaica. *Journal of Animal Ecology* **70**, 546-560.

Johnstone R., Kirkby T., Stone P. & Minton C. (2003) *White-tailed Black-Cockatoos: Identification Challenges and Changes in Distribution and Status, and links with a Community Program - Cockatoo Care.* Conserving Carnaby's Black-Cockatoo: future directions: proceedings from a conservation symposium, Perth, Western Australia, 2 July 2003.

Johnstone R.E. & Kirkby T. (1999) Food of the forest red-tailed black cockatoo *Calyptorhynchus banksii naso* in south-west Western Australia. *The Western Australian Naturalist* **22**, 167-177

Johnstone R.E. & Storr G.M. (1998) *Handbook of Western Australian Birds Volume 1, Non-passerines (Emu to Dollarbird).* Western Australian Museum, Perth.

Joseph L. (1982) The Glossy Black Cockatoo on Kangaroo Island. *Emu* **82,** 46–9.

Keeley J. E. & Zedler P. H. (1978) Reproduction of chaparral shrubs after fire: a comparison of sprouting and seeding strategies. *American Midland Naturalist* **99**, 142–161.

Keeley J.E. (1986) Resilience of Mediterranean shrub communities to fires. In: Dell, B., Hopkins, A.J.M. & Lamont, B.B. (eds.) *Resilience in Mediterranean-type ecosystems,* Junk Publishers, Dordrecht, 95-112.

Keighery G.J., Coates D.J. & Gibson N. (1994) Future ecosystems – ecological balance (ecological impact of disease causing fungi in south-western Australia). *Journal of the Royal Society of Western Australia* **77**, 181-184.

Knox B., Ladiges P., Evans B. & Saint R. (2001) *Biology*, 2nd edn. McGraw-Hill, Sydney.

Kuo J., Hocking P.J. & Pate J.S. (1982) Nutrient reserves in seeds of Proteaceous species from south-western Australia. *Australian Journal of Botany* **30**, 231-249.

Lack D.R.R.S. (1954) *The Natural Regulation of Animal Numbers*. Oxford University Press, Oxford.

Lamont B.B. & Baker M.J. (1988) Seed bank dynamics of a serotinous, fire-sensitive *Banksia* species. *Australian Journal of Botany* **36**, 193-203.

Lamont B.B. & Connell S.W. (1996) Biogeography of *Banksia* in southwestern Australia. *Journal Biogeography* **23**, 295-309.

Lamont B.B., Enright N.J., Witowski E.T.F & Groeneveld J. (2007) Conservation biology of banksias: insight from natural history simulation modelling. *Australian Journal of Botany* **55**, 280–292

Lamont B.B. & Groom P.K. (1998) Seed and seedling biology of the woody-fruited Proteaceae. *Australian Journal of Botany*, **46**, 387–406.

Lamont B.B., Groom P.K., Richards M.B. & Witkowski E.T.F. (1999) Recovery of *Banksia* and *Hakea* communities after fire in mediterranean Australia – the role of species identity and functional attributes. *Diversity and Distributions* **5**, 15-26.

Lamont B.B., Maitre D.S.L., Cowling R.M. & Enright N.J. (1991) Canopy seed storage in woody plants. *The Botanical Review* **57**, 277-317.

Lamont B.B. & Markey A. (1995) Biogeography of fire-killed and resprouting *Banksia* species in southwestern Australia. *Australian Journal of Botany* **43**, 283–303.

Lamont B.B., Olesen J.M. & Peter B.J. (1998). Seed production, pollinator attractants and breeding system in relation to fire response—Are there reproductive syndromes among co-occurring Proteaceous shrubs? *Australian Journal of Botany* **46**, 377–85.

Lamont, B.B. & Van Leeuwen S.J. (1988). Seed production and mortality in a rare *Banksia* species. *Journal of Applied Ecology* **25**, 551-559.

Lamont B.B. & Witkowski E.T.F. (1995) A test for lottery recruitment among four *Banksia* species based on their demography and biological attributes. *Oecologia* **101**, 299-308.

Lott J.N.A. & Buttrose M.S. (1978) Location of reserves of mineral elements in seed protein bodies: macadamia nut, walnut and hazel nut. *Canadian Journal of Botany* **56**, 2072-2082.

MacArthur R. H. & Pianka E. R. (1966) On the optimal use of a patchy environment. *American Naturalist* **100**, 603–609.

Macreadie P.I., Hindell J.S., Keough M.J., Jenkins G.P. & Connolly R.M. (2010) Resource distribution influences positive edge effects in a seagrass fish. *Ecology* **91,** 2013–2021

Marchant N.G., Wheeler J.R., Rye B.L., Bennett E.M., Lander N.s. & Macfarlane T.D. (1987) Flora of the Perth Region. Western Australia Herbarium, Department of Agriculture, Western Australia.

Mast A.R. (1998) Molecular systematics of subtribe Banksiinae (*Banksia* and *Dryandra*: Proteaceae) based on cpDNA and nrDNA sequence data: implications for taxonomy and biogeography. *Australian Systematic Botany* **11**, 321-342.

Mast A.R. & Givnish T.J. (2002) Historical biogeography and the origin of stomatal distributions in *Banksia* and *Dryandra* (Proteaceae) based on their cpDNA phylogeny. *American Journal of Botany* **89**, 1311–1323.

Mast A.R., Jones E.H. & Havery S.P. (2005) An assessment of old and new DNA sequence evidence for the paraphyly of *Banksia* with respect to *Dryandra* (Proteaceae). *Australian Systematic Botany* **18**, 75–88.

Mast A.R. & Thiele K. (2007) The transfer of *Dryandra* R. Br. to *Banksia* L.f. (Proteaceae). *Australian Systematic Botany* **20**, 63–71.

Mawson P. & Johnstone R. (1997). Conservation status of parrots and cockatoos in Western Australia. *Eclectus* **3**, 21-23.

Mawson P.R. & Long J.L. (1994) Size and age parameters of nest trees used by four species of parrot and one species of cockatoo in south-west Australia. *Emu*. **94**, 149-155.

McArthur W. M. & Bettenay E. (1960) *The development and distribution of the soils of the Swan coastal plain, Western Australia.* Commonwealth Scientific and Industrial Research Organisation, Melbourne, Australia.

Mattiske E. M. & Havel J. J. (1998) *Vegetation Complexes of the South-west Forest Region of Western Australia*. Maps and report prepared as part of the Regional Forest Agreement. Western Australia for the Department of Conservation and Land Management and Environment Australia, Western Australia.

Monaghan P., Uttley J.D., Burns M.D., Thaine C. & Blackwood J. (1989)The Relationship between food supply, reproductive effort and breeding success in Arctic Terns *Sterna paradisaea. Journal of Animal Ecology.* **58**, 261-274

Morrison M.L., Marcot B.C. & Mannan R.W. (1998) *Wildlife-Habitat Relationships* 2nd ed. University of Wisconsin Press, Madison.

Mörtberg U.M., Balfors B. & Knol W.C. (2007) Landscape ecological assessment: A tool for integrating biodiversity issues in strategic environmental assessment and planning. *Journal of Environmental Management* **82**, 457-470.

Myers N., Mittermeier R. A., Mittermeier C. G, da Fonseca G. A. B. & Kent J. (2000) Biodiversity hotspots for conservation priorities. *Nature* **403,** 853-858.

Naulleau G. & Bonnet X. (1996) Body condition threshold for breeding in a viviparous snake. *Oecologia*, **107** (3), 301-306.

Niklas K. (1994) *Plant allometry. The scaling of form and process*. Chicago: University of Chicago Press.

Pate J.S, Rasins E., Rullo J. & Kuo J. (1985) Seed nutrient reserves of Proteaceae with special reference to protein bodies and their inclusions. *Annals of Botany* **57**, 747-770.

Pate J.S., Froend R.H., Bowen B.J., Hansen A. & Kuo J. (1990) Seedling growth and storage characteristics of seeder and resprouter species of Mediterranean-type ecosystems of S. W. Australia. *Annals of Botany* **65**, 585-601.

Pitman A.J. & Perkins S.E. (2008) 'Regional projections of future seasonal and annual changes in rainfall and temperature over Australia based on skill-selected AR4 models', *Earth Interactions* 12, Paper No. 12, 1–50.

Perry D.H. (1948) Black Cockatoos and pine plantations. *Western Australian Naturalist* **1**, 133-135.

Reed, B.C. Brown, J.F., Vanderzee, D., Loveland T.R., Merchant J.W., & Ohlen D.O. (1994) Measuring phenological variability from satellite imagery. *Journal of Vegetation Science* **5**, 703-714.

Richards M. B. & Lamont B. B. (1996) Post-fire mortality and water relations of three congeneric shrub species under extreme water stress—a trade-off with fecundity? *Oecologia* **107**, 53–60.

Robinson K. & Holmes R.T. (1982). Foraging behaviour of forest birds: the relationships among search tactics, diet, and habitat structure. *Ecology* **63,** 1918-1931.

Rockel B. A., McGann L. R. & Murray D. I. L. (1982). *Phytophthora cinnamomi* causing death of *Dryandra sessilis* on old dieback sites in the jarrah forest. *Australasian Plant Pathology* **11** (4), 49–50.

Rourke J. & Wiens D. (1977) Convergent floral evolution in South African and Australian Proteaceae and its possible bearing on pollination by nonflying mammals. *Annals of the Missouri Botanical Garden* **64**, 1-17.

Rowley I. & Chapman G. 1991. The breeding biology, food, social organisation, demography and conservation of the Major Mitchell or Pink Cockatoo, *Cacatua leadbeateri*, on the margin of the Western Australian wheatbelt. *Australian Journal of Zoology* **39,** 211-261.

Salisbury E.J. (1926) The geographical distribution of plants in relation to climatic factors. *The Geographical Journal* ***67***, 312-335.

Saunders D.A. (1974) The occurrence of the White-tailed Black Cockatoo, *Calyptorhynchus baudinii*, in *Pinus* plantations in Western Australia. *Australian Wildlife Research* **1**, 45-54.

Saunders D.A. (1979a) The availability of tree hollows for use as nest sites by White-tailed Black Cockatoos. *Australian Wildlife Research* **6**, 205-216.

Saunders D.A. (1979b). Distribution and taxonomy of the White-tailed and Yellow-tailed black-cockatoos *Calyptorhynchus* spp. *Emu* **79**, 215-227.

Saunders D. A. (1980) Food and movements of the short-billed form of the White-tailed Black Cockatoo. *Australian Wildlife Research* **7**, 257-69.

Saunders D.A. (1982) Breeding behaviour and biology of the short-billed form of the white-tailed black-cockatoo. *Australian Wildlife Research* **6**, 205-216.

Saunders D.A. (1986). Breeding season, nestling success and nestling growth in Carnaby's cockatoo, *Calyptorhynchus funereus latirostris*, over 16 years at Coomallo Creek, and a method for assessing the viability of populations in other areas. *Australian Wildlife Research* **13,** 261-273.

Saunders D. A. (1990) Problems of survival in an extensively cultivated landscape: the case of Carnaby's Cockatoo *Calyptorhynchus funereus latirostris*. *Biological Conservation* **54**, 277-90.

Saunders D.A. (2002) *From vermin to landscape ecology: The tale of Carnaby's cockatoo.* Surrey Beatty & Sons Pty. Ltd.

Saunders D.A. & Ingram J.A. (1987). Factors affecting survival of breeding populations of Carnaby's cockatoo *Calyptorhynchus funereus latirostris* in remnants of native vegetation. In *Nature Conservation: The Role of Remnants of Native Vegetation*. (Eds. D.A. Saunders, G.W. Arnold, A.A. Burbidge and A.J.M. Hopkins) pp. 249-258. Surrey Beatty and Sons, Chipping Norton.

Saunders D.A. & Ingram J.A. (1995). *Birds of Southwestern Australia: An Atlas of Changes in the Distribution and Abundance of Wheatbelt Avifauna*. Surrey Beatty and Sons, Chipping Norton.

Saunders D.A. & Ingram J.A. (1998). Twenty-eight years of monitoring a breeding population of Carnaby's cockatoo. *Pacific Conservation Biology* **4,** 261-270.

Saunders D.A., Mawson P. & Dawson R. (2011) The impact of two extreme weather events and other causes of death on Carnaby's Black Cockatoo: a promise of things to come for a threatened species? *Pacific Conservation Biology* **17**, 141-148.

Saunders D.A., Rowley I. & Smith G.T. (1985) The effects of clearing for agriculture on the distribution of cockatoos in the southwest of Western Australia. In: *Birds of Eucalypt Forests and Woodlands: Ecology, Conservation, Management*. (Eds. A. Keast, H.F. Recher, H. Ford and D. Saunders) pp. 309-321. Surrey Beatty & Sons, Chipping Norton.

Schwartz M.D. (1994) Monitoring global change with phenology: the case of the spring green wave. *International Journal of Biometeorology* **38**, 18-22.

Scott J. K. (1982) The impact of destructive insects on reproduction in six species of *Banksia* L.f. (Proteaceae). *Australian Journal of Zoology* **30**, 901-921.

Scott J.K. & Black R. (1981) Selective predation by White-Tailed Black Cockatoos on fruit of *Banksia attenuata* containing the seed-eating weevil *Althitopis nivea*. *Australian Wildlife Research* **8**, 421-30.

Sedgwick E. H. (1955) Bird-life at Wooroloo. Part II. *Western Australian Naturalist* **5**. 63-70.

Semeniuk V and Glassford D.K. (1989) Bassendean and Spearwood dunes: their geomorphology, stratigraphy and soils as a basis for habitats of banksia woodlands. *Journal of the Royal Society of Western Australia* **71**, 87-88.

Serventy D. L. (1948) The birds of the Swan River district, Western Australia. *Emu* **47**, 241-286.

SEWPAC (2012) EPBC Act referral guidelines for three threatened black cockatoo species: Carnaby's cockatoo (endangered) *Calyptorhynchus latirostris*, Baudin's cockatoo (vulnerable) *Calyptorynchus baudinii*, Forest red-tailed black cockatoo (vulnerable) *Calyptorynchus banksii naso.* Retrieved October 2012, from SEWPAC website: http://www.environment.gov.au/epbc/publications/wa-black-cockatoos.html

Shah B. (2006) *Conservation of Carnaby's cockatoo on the Swan coastal plain, Western Australia*. Birds Australia WA, Perth.

Shearer B.L. (1990) Dieback of native communities caused by *Phytophthora* species - A major factor affecting land use in south-western Australia. *Land and Water research News* **5**, 15-26.

Shearer B.L., Crane C.E., Barrett S. & Cochrane A. (2007) *Phytophthora cinnamomi* invasion, a major threatening process to conservation of flora diversity in the South-

west Botanical Province of Western Australia. *Australian Journal of Botany* **55**, 225-238.

Shearer B. L. & Dillon M. (1996a) Impact and disease centre characteristics of *Phytophthora cinnamomi* infestations of banksia woodlands on the Swan Coastal Plain, Western Australia. *Australian Journal of Botany* **44**, 79-90.

Shearer B.L. & Dillon M. (1996b) Susceptibility of plant species in banksia woodlands on the Swan coastal plain, Western Australia, to infection by *Phytophthora cinnamomi*. *Australian Journal of Botany* **44**, 433-445.

Shearer B.L. & Hill T.C. (1989) Diseases of banksia woodlands on the Bassendean and Spearwood Dune Systems. *Journal of the Royal Society of Western Australia* **71**, 113-114.

Sherry T.W. (1984) Comparative dietary ecology of sympatric insectivorous Neotropical flycatchers (Tyrannidae). *Ecological Monographs* **54,** 313-338.

Shipley B. & Dion J. (1992) The allometry of seed production in herbaceous angiosperms. *The American Naturalist* **139**, 467-483

Speck N.H. (1958) The vegetation of the Darling-Irwin botanical districts, and an investigation of the distribution patterns of the family Proteaceae, South Western Australia. Ph.D. thesis, University of Western Australia.

Stannage T. (1979) *The people of Perth: A social history of Western Australia's capital city*. Perth City Council, Perth, Western Australia.

State of the Environment Report Western Australia (2007) Human Settlements. In: *State of the Environment Report Western Australia*. Retrieved March 2010 from State of the Environment WA website: http://www.soe.wa.gov.au/

Stock W.D., Finn H., Parker J. & Dods K. (2013) Pine as fast food: Foraging ecology of an endangered cockatoo in a forestry landscape. PLoS ONE **8**(4): e61145.

Stock W.D., Pate J.S. & Delfs J. (1990) Influence of seed size and quality on seedling development under low nutrient conditions in five Australian and South African members of the Proteaceae. *Journal of Ecology* **78**, 1005–1020.

Stock W.D., Pate J.S. & Rasins E. (1991) Seed developmental patterns in *Banksia attenuata* R. Br. and *B. laricina* C. Gardner in relation to mechanical defence costs. *New Phytologist* **117**, 109-114.

Studds C.E. & Marra P. (2011) Rainfall-induced changes in food availability modify the spring departure programme of a migratory bird. *Proceedings of the Royal Society of B - Biological Sciences* **278**, 3437–3443.

Tataranni P.A., Larson D.E. Snitker S. & Ravussin E. (1995) Thermic effect of food in humans: methods and results from use of a respiratory chamber. *American Journal of Clinical Nutrition* **61**, 1013–1019.

Taylor A. & Hopper S.D. (1988) *The Banksia Atlas*. *Australian Flora and Fauna Series*. 8. Canberra: AGPS.

Turner M.G. (1989) Landscape Ecology: The effect of pattern on process. *Annual Review of Ecology and Systematics* **20**, 171-197.

Valentine L. & Stock W. (2008) *Food resources of Carnaby's cockatoo (Calyptorhynchus latirostris) in the Gnangara Sustainability Strategy study area*. Centre for Ecosystem Management, Edith Cowan University. Retrieved February 2010, from the Gnangara Sustainability Study web site: http://portal.water.wa.gov.au/portal/page/portal/gss/Reports

Valera F., Wagner R., Romero-Pujante M., Guttiérrez J.E. & Rey P.J. (2005) Dietary specialization on high protein seeds by adult and nestling serins. *The Condor* **107**, 29-40.

van Leeuwen S.J. & Lamont B.B. (1986) *Conservation status and reproductive biology of* Banksia tricuspis*.* Report to World Wildlife Fund (Australia), Curtin, Bentley.

van Leeuwen S.J. & Lamont B.B. (1996). Floral damage by animals and its impact on reproductive success in *Banksia tricuspis* Meisner (Proteaceae). In *Gondwanan Heritage: Past, Present and Future of the Western Australian Biota* (eds SD Hopper, JA Chappill, MS Harvey *et al*.). Surrey Beatty, Sydney. pp. 196–202.

van Staden J. & Brown N.A.C. (1977) Studies on the germination of South African Proteaceae – a review. *Seed Science and Technology* **5**, 633-643.

van Staden J. & Comins N.R. (1976) Energy dispersive x-ray analysis of protein bodies in *Protea compacta* cotyledons. *Planta* **130**, 219-221.

Walker L. R. (2011). Integration of the study of natural and anthropogenic disturbances using severity gradients. *Austral Ecology* **36**, 916-922.

Way S. (2006) *Strategic management of Aleppo Pines on Lower Eyre Peninsula to maximize biodiversity conservation outcomes*. Department of Environment and Heritage, South Australia.

Weller R. (2009) *Boom Town 2050 - scenarios for a rapidly growing city*. University of Western Australia Publishing, Crawley, WA.

Western Australian Herbarium (1998-). *Florabase – The Western Australian Flora*. Department of Environment and Conservation. Retrieved August 2012, from DEC website: http://florabase.dec.wa.gov.au

Western Australian Planning Commission (2010) *Directions 2031 and beyond: metropolitan planning beyond the horizon*. Retrieved August 2012, from the Planning Western Australia web site: www.planning.wa.gov.au

Whelan R.J. & Burbidge A.H. (1980) Flowering phenology, seed set and bird pollination of five Western Australian *Banksia* species. *Australian Journal of Ecology* **5**, 1-7.

Williams J.B., Withers P.C., Bradshaw S.D. and Nagy K.A. (1991) Metabolism and water fluxes of captive and free-living Australian parrots. *Australian Journal of Zoology* **39**, 131-142.

Wills J.W. (2003) Using Banksia (Proteaceae) node counts to estimate time since fire. *Australian Journal of Botany* **51**, 239-242.

Withers P.C. (1982) Effect of diet and assimilation efficiency on water balance for two desert rodents. *Journal of Arid Environments* **5**, 375-384.

Witkowski E.T.F., Lamont B.B. & Connell S.J. (1991) Seed bank dynamics of three co-occurring banksias in south coastal Western Australia: the role of plant age, cockatoos, senescence and inter-fire establishment. *Australian Journal of Botany* **39**, 385-397.

Appendix

Appendix 1: Study site details (Government of Western Australia 2000; Spatial layers, DEC GIS Corporate Data: MRS – Bushforever- Site Boundaries (Department of Planning, 2011); Existing DEC Estate Managed Lands and Waters (DEC, 2012); State Cadastral Data Base (Landgate, 2012)

Study Site	ID	Local Municipality	Tenure	Vested	Managed	Coordinates	Reserve/Site Area (ha)	Bush Forever Area (ha)	Landform and Soils	Vegetation Complex *	Characteristics
Beeliar Regional Park – Thomsons Lake & Harry Warring Marsupial Reserve	BR	City of Cockburn	Crown Land (R15556 and 29241)	CC	DEC and University of Western Australia	115.830156 -32.155321	882	1 025	Bassendean, Spearwood Dunes & Wetlands	1; 4; 7; 15	Bush Forever sites 391 and 392 form important fauna conservation, research and drainage reserves. Both reserves are enclosed by feral proof fencing. Harry Waring Marsupial Reserve is managed on-site by the University of Western Australia. Open woodlands of *E. marginata, B. attenuata* and *B. menziesii* in upland areas with *E. rudis* and *Melaleuca* species dominating wetland areas with sedgeland understory. Thomsons Lake moderate recreational use.
Bold Park	BP	Town of Cambridge	Crown Land (R45409)	BGPA	Bold Park Board	115.770462 -31.947559	437	464	Quindalup & Spearwood Dunes	4; 7	Bush Forever 312 Bold Park and adjacent bushland, City Beach Area. Uplands, sands derived from Tamala Limestone with open *Eucalyptus gomphocephala* forest, low *B. attenuata* and *B. menziesii* woodlands and open and closed heaths. Quindalup dunes open mixed heath. *Ehrharta calycina* dominant weed understory. High recreational use.
Buller Nature Reserve	BN	Shire of Waroona	Crown Land (R22199)	CC	DEC	115.829112 -32.882764	301	N/A	Bassendean Dunes	10	Open *E. marginata* forest with low B. attenuata woodland. Most southern extent of *B. menziesii*, though sparse. Powerlines dissecting reserve into east and west portions. *Phytophthora* disease present at various locations adjacent to tracks.
Cardup Nature Reserve	CN	Shire of Serpentine-Jarrahdale	Crown Land (R2457)	CC	DEC	115.989118 -32.246120	75	90	Bassendean Dunes & Pinjarra Plain	6	Located, 1.7km south-west of Byford. Cardup Nature Reserve and adjacent bushland forms Bush Forever site 352. Open Eucalypt woodland with Banksia and mixed shrubland understory. *Phytophthora* disease present at various locations.

Craigie Bushland (Open Space)	CB	City of Joondalup	Crown Land (R32858)	City of Joondalup	City of Joondalup	115.777987 -31.793112	54	87	Quindalup & Spearwood Dunes	4; 7	Whitfords Avenue Bush Forever site 303. Bushland covers an area of 215 ha but proposed boundary circumscribes 139.5ha. Woodlands of *B. prionotes* and *E. gomphocephala* on Quindalup dunes. On Spearwood dunes low open woodlands of *B. attenuata, B. menziesii,* or *Allocasuarina* with scattered eucalypts; Open forest of *E. marginata, E. gomphocephala* or *C. calophylla.* Moderate recreational use.
Jandakot Regional Park - Acourt Road Bushland	JR	City of Canning and City of Cockburn	Crown Reserve	WA Planning Commission	DEC	115.903490 -32.107352	278	307	Bassendean Dunes, Pinjarra Plain & Wetlands	1	Acourt Road Bushland in Banjup forms Bush Forever site 389. Low woodlands dominated by *B. attenuata*, with a scattering of *B. ilicifolia* and *B. menziesii*. Damplands dominated by *E. rudis, M. rhaphiophylla, M. presianna* and *Kunzea glabrescens.*
Kingia	EL	Shire of Serpentine-Jarrahdale	Freehold	Alan and Marrion Elliott	Alan and Marrion Elliott	115.881022 -32.448909	98	447	Bassendean Dunes, Pinjarra Plain & Wetlands	1; 10	Forms part of Bush Forever site 77, Yangedi Swamp, Keysbrook. *B. attenuata, B. menziesii* and *B. ilicifolia* open woodland in upland areas. *Melaleuca* spp. dominant wetland areas. *Phytophthora* disease present throughout.
Kings Park	KP	City of Perth	Crown Land (R1720)	BGPA	Kings Park Board	115.831453 -31.962531	393	406	Spearwood Dunes	7	Located on the Swan River to the west of the CBD, Bush Forever site 317 Kings Park. Banksia woodland with mixed Eucalypt overstorey. High recreational use.
Leda Nature Reserve	LN	Town of Kwinana and City of Rockingham	Crown Land (R33581)	CC	DEC	115.807642 -32.277444	436	439	Quindalup, Spearwood, Bassendean Dunes & Wetlands	1; 4; 7; 8; 12	Bush Forever site 349, Leda and adjacent bushland. Dissected into blocks by gas power, railway and road easements. Weed invasion high with *Ehrharta calycina* dominant weed understory. Woodlands over sedgelands in Holocene dune swales, *M. raphiophylla- Gahnia trifida* wetlands, Eucalypt woodlands, *B. attenuata-E. marginata* woodlands and *E. gomphocephala*-mixed banksia woodlands.

Lowlands	LL	Shire of Serpentine-Jarrahdale	Freehold	Midge Richardson	Midge Richardson and Mark Angeloni	115.912246 -32.330665	1 065	1 065	Bassendean Dunes, Pinjarra Plain & Wetlands	1;6; 10; 14	Bush Forever site 368 - Lowlands Bushland Eastern Block, Peel Estate. *E. rudis* woodlands over sedgelands with *M. pressiana* in damplands, *B. attenuata* and *B. menziesii* woodlands with emergent *E. marginata* and *C. calophylla*. Low weed invasion. *Phytophthora* disease present along main access track.
McLarty Nature Reserve	ML	Shire of Murray	Crown Land (R24739)	CC	DEC	115.704186 -32.693823	48	N/A	Spearwood Dunes & Wetlands	4	McLarty Nature Reserve adjoins McLarty Lake Nature Reserve, adjacent to the Harvey Estuary. Upland areas dominated by banksia woodland with emergent Eucalypts, wetlands dominated by *Melaleuca* spp, and *K. glabrescens.*
Melaleuca Conservation Park	MC	Shire of Swan	State Forest	CC	DEC	115.920129 -31.687894	3 264	4 261	Bassendean Dunes & Wetlands	2; 3; 13	Melaleuca Park and adjacent bushland Bullsbrook forms Bush Forever site 399. Melaleuca Park forms part of the Gnangara – Moore River State Forest, which covers an area of 66 027 ha. Mixed banksia woodland with intermittent *E. todtiana, E. marginata, N. floribunda* or *M. pressiana* over mixed open heaths to low shrub. Melaleuca species and *E. rudis* dominate wetland areas.
Modong Nature Reserve	MN	Shire of Serpentine-Jarrahdale	Crown Land (R25886)	CC	DEC	115.897663 -32.227140	156	162	Bassendean Dunes, Pinjarra Plain &Wetlands	1	Bush Forever site 348. Forms part of Jandakot Regional Park. *M. pressiana* and *K. glabrescens* dominate wet areas. Uplands dominated by *B. attenuata* and *B. menziesii* woodlands. *Phytophthora* disease scattered through reserve.
Mt Henry Peninsula	MH	City of South Perth	Freehold	Aquinas College	Aquinas College	115.861429 -32.031467	9	10	Spearwood Dunes & Pinjarra Plain	1	Bush Forever number 227. Mixed banksia woodlands *of B. attenuata, B. menziesii* and *B. sessilis. Casuarina obesa* dominate vegetation in wetlands to the west. Bounded by the Kwinana Freeway and Canning River on three sides.
Nine Mile Nature Reserve	NM	Shire of Murray	Crown Land (R16907)	CC	DEC	115.776824 -32.738010	113	N/A	Bassendean Dunes & Wetlands	10	Nine Mile Nature Reserve is surrounded by farming land, predominately cattle. Upland areas dominated by banksia woodland with emergent Eucalypts, wetlands dominated by *Melaleuca* spp, and sedgelands.

Rockingham Regional Park - Paganoni Reserve	PN	City of Rockingham	Crown Land	City of Rockingham	DEC	115.788008 -32.444279	697	708	Bassendean, Spearwood Dunes, Pinjarra Plain & Wetlands	4; 7; 15	Paganoni Swamp and adjacent bushland forms Bush Forever site 395. *M. rhaphiophylla – G. trifida* wetlands. *B. attenuata - E. marginata* woodlands and *E. gomphocephala - Agonis flexuosa* woodlands.
Star Swamp	SS	City of Stirling	Crown Land (R39962)	City of Stirling	City of Stirling	115.762490 -31.854234	97	97	Spearwood Dunes & Wetlands	4; 8	Bush Forever site 204, Start Swamp Reserve and adjacent bushland. Vegetation communities include *M. rhaphiophylla* low closed forest, *E. marginata and E. gomphocephala* woodlands and *B. attenuata* and *B. menziesii woodlands.* High recreational use.
State Forest (North of Yanchep)	SF	Shire or Wanneroo and Gingin	State Forest	CC	DEC/FPC	115.620706 -31.410663	5 752	10 087	Bassendean Dunes, Spearwood Dunes, Quindalup Dunes Pinjarra Plain & Wetlands	2; 3; 5; 8; 16	Large area forming parts of various Bush Forever sites including Chitty Road Bushland Pinjar site 398 and Wilbinga-Caraban Bushland site 406. Area forms part of the Gnangara-Moore River State Forest which covers an territory of 6602.8 ha. Mixed banksia woodland, emergent *N. floribunda* and Eucalypts, with mixed shrubland understory. Vegetation height reduced towards the coast due to shallow soils with limestone protrusions vegetation becoming closed communities of mixed species.
Whiteman Park	WP	Shire of Swan	Freehold	WA Planning Commission	Whiteman Park Board	115.941518 -31.824314	3 285	3 285	Bassendean Dunes, Pinjarra Plain & Wetlands	1; 10	Bush Forever 304, Whiteman Park has a number of different landuses from conservation and recreation to cattle grazing. Bushland dominated by mixed banksia woodland in upland areas with wetlands dominated by *E. rudis, M. pressiana* and *M. rhaphiophylla* open forest. *Phytophthora* disease scattered throughout.
Yalgorup National Park - Northern section	YL	Shire of Murray	Crown Land (R11710)	CC	DEC	115.667285 -32.844894	13 052	N/A	Quindalup & Spearwood Dunes	4; 8	Lying along the coast, the northern half of Yalgorup National Park (White Hills Road to Tim's Thicket Road) vegetation is dominated by *B. attenuata* and emergent Eucalypts with mixed shrubland understory higher in the landscape with coastal limestone areas dominated by *Acacia* spp.

Yanchep National Park	YN	Shire of Wanneroo	Crown Land (R9868)	CC	DEC	115.681686 -31.536455	2877	2900	Quindalup Dunes, Spearwood Dunes & Wetlands	4; 5; 8; 15	Yanchep National Park and adjacent bushland form Bush Forever site 288. *B. attenuata* and *B. menziesii* dominated woodlands and *E. gomphocephala* and *E. marginata* open forest. Limestone ridges covered by *B. sessilis, Hakea trifurcata, Calothamnus quadrifidus* and *Melaleuca* spp. Wetland areas characterised by *E. rudis, M. rhaphiophylla* and mixed sedgeland. High recreational use around visitor centre.

CC – Conservation Commission; DEC - Department of Environment and Conservation; BGPA - Botanic Gardens and Parks Authority; FPC - Forest Products Commission; DEP – Department of Planning

*Vegetation complex legend Appendix 2.

Appendix 2: Vegetation complex ID (Government of Western Australia 2000)

Landform	Vegetation (Heddle) Complex	ID	Description
Pinjarra Plain	Guildford Complex	1	Mixture of open forest to tall open forest of *C. calophylla-E. wandoo - E. marginata* and woodland of *E. wandoo*.
Pinjarra Plain	Dardanup Complex	2	Mosaic of vegetation types characteristic of adjacent vegetation complexes such as Serpentine, Southern River and Guildford.
Pinjarra Plain	Serpentine River Complex	3	Closed scrub of Melaleuca species and fringing woodland of *E. rudis - M. rhaphiophylla* along streams.
Pinjarra Plain	Yanga Complex	4	Predominantly a closed scrub Melaleuca species and low open forest of *C. obesa* on the flats subject to inundation. On drier sites the vegetation reflects the adjacent complexes of Bassendean.
Bassendean	Bassendean Complex North	5	Vegetation ranges from a low open forest and low open woodland of banksia species, *E. todtiana* to low woodland of Melaleuca species and sedgelands which occupy moister sites.
Bassendean	Bassendean Complex Central and South	6	Vegetation ranges from woodland of *E. marginata- A. fraseriana-Banksia* spp. to low woodland of *Melaleuca* spp., and sedgelands on the moister sites.
Bassendean	Bassendean Complex North - Transition Vegetation Complex	7	A transition complex of low open forest and low woodland of Banksia species - E. todtiana on a series of high sand dunes. The understory species reflect similarities with both the Bassendean-North and Karrakatta-North vegetation complexes.
Bassendean	Southern River Complex	8	Mosaic of vegetation from adjacent vegetation complexes of Bassendean, Karrakatta, Sothern River and Vasse.
Spearwood	Cottesloe Complex North	9	Predominantly low open forest and low woodland of *B. attenuata - B. menziesii - E. todtiana*; closed heath on the Limestone outcrops.
Spearwood	Cottesloe Complex Central and South	10	Mosaic of woodland of E. gomphocephala and open forest of *E. gomphocephala, E marginata - C. calophylla*; closed heath on the Limestone outcrops.
Spearwood	Karrakatta Complex North	11	Predominantly low open forest and low woodland of *Banksia* spp. *E. todtiana*, less consistently open forest of *E. gomphocephala - E. todtiana* - Banksia species.
Spearwood	Karrakatta Complex Central and South	12	Predominantly open forest of *E. gomphocephala - E. marginata - C. calophylla* and woodland of E. marginata - Banksia species.
Spearwood	Yoongarillup Complex	13	Woodland to tall woodland of E. gomphocephala with *A. flexuosa* in the second storey. Less consistently an open forest of *E. gomphocephala - E. marginata - C. calophylla.*
Quindalup	Quindalup Complex	14	Coastal Dune complex consisting mainly two alliances - the strand and fore-dune alliance and the mobile and stable dune alliance.
Wetlands	Herdsman Complex	15	Sedgelands and fringing woodland of *E. rudis - Melaleuca* species.
Wetlands	Pinjar Complex	16	Vegetation ranges from woodland of *E. marginata - Banksia* spp. to a fringing woodland of *E. rudis - M. preissiana* and sedgelands.

Appendix 3: Quadrat summary information. Time since last fire (TSLF) categories: 1 = ≤ 5 years; 2 = 6-10 years; 3 = 11-15 years; 4 = 16-20 years; and 5 = ≥ 21 years (Spatial data DEC GIS Corporate Data: Soil-landscape systems mapping south west of Western Australia v4 (Agriculture Western Australia 2006); DEC Fuel Age spatial data (DEC 2012); Project Dieback NRM (DEC Forest Management Branch 2005)).

Quadrat ID	TSLF Category	Vegetation Complex	Landform Type	Elevation (m)	*P. cinnamomi*
BN1	3	8	Bassendean	10-15	Present
BN2	3	8	Bassendean	20-25	Absent
BN3	3	8	Bassendean	15-20	Present
BN4	3	8	Bassendean	15-20	Present
BN5	3	8	Bassendean	15-20	Absent
BN6	3	8	Bassendean	20-25	Absent
BP1	5	10	Quindalup	20-25	Absent
BP2	5	10	Quindalup	25-30	Absent
BP3	5	10	Quindalup	45-50	Absent
BR1	5	6	Bassendean	25-30	Absent
BR2	5	6	Bassendean	20-25	Absent
BR3	5	6	Bassendean	25-30	Absent
CB1	5	12	Spearwood	20	Absent
CB2	5	12	Spearwood	10-15	Absent
CB3	5	12	Spearwood	20	Absent
CN1	4	6	Bassendean	50-55	Absent
CN2	4	6	Bassendean	40-45	Absent
CN3	4	6	Bassendean	40-45	Absent
EL1	5	6	Bassendean	25-30	Absent
EL2	5	6	Bassendean	25-30	Absent
EL3	5	6	Bassendean	25-30	Absent
JR1	5	6	Bassendean	30-35	Absent
JR2	5	6	Bassendean	25-30	Absent
JR3	5	6	Bassendean	25-30	Absent
KP1	1	12	Spearwood	20-25	Absent
KP2	1	12	Spearwood	45-50	Absent
KP3	1	12	Spearwood	45-50	Absent
KP4	4	12	Spearwood	50	Absent
KP5	4	12	Spearwood	45-50	Absent
KP6	4	12	Spearwood	40-45	Absent
LL1	5	6	Bassendean	15-20	Absent
LL2	5	6	Bassendean	15-20	Absent
LL3	5	6	Bassendean	15-20	Absent
LN1	5	12	Spearwood	10-15	Absent
LN2	5	12	Spearwood	15-20	Absent
LN3	5	12	Spearwood	10-15	Absent
MC1	3	5	Bassendean	65-70	Present
MC2	3	5	Bassendean	60-65	Present
MC3	3	5	Bassendean	70-75	Present
MC4	3	5	Bassendean	70-75	Absent
MC5	3	5	Bassendean	60-65	Absent
MC6	3	5	Bassendean	65-70	Absent

MH1	3	6	Spearwood	15-20	Absent
MH2	3	6	Spearwood	15-20	Absent
MH3	3	6	Spearwood	5-10	Absent
ML1	5	10	Spearwood	5-10	Absent
ML2	5	10	Spearwood	0-5	Absent
ML3	5	10	Spearwood	0-5	Absent
MN1	5	6	Bassendean	25-30	Absent
MN2	5	6	Bassendean	25-30	Present
MN3	5	6	Bassendean	30-35	Absent
NM1	5	8	Bassendean	15-20	Absent
NM2	5	8	Bassendean	10-15	Absent
NM3	5	8	Bassendean	5-10	Absent
PR1	5	12	Spearwood	25-30	Absent
PR2	5	12	Spearwood	15-20	Absent
PR3	5	12	Spearwood	15-20	Absent
SF1	2	10	Spearwood	35-40	Absent
SF2	2	11	Spearwood	60-65	Absent
SF3	2	10	Spearwood	50-55	Absent
SF4	2	10	Spearwood	55-60	Absent
SF5	2	10	Spearwood	45-50	Absent
SF6	2	10	Spearwood	35-40	Absent
SS1	4	10	Spearwood	10-15	Absent
SS2	4	10	Spearwood	10-15	Absent
SS3	4	10	Spearwood	10-15	Absent
SS4	1	10	Spearwood	25-30	Absent
SS5	1	10	Spearwood	15-20	Absent
SS6	1	10	Spearwood	15-20	Absent
WP1	3	6	Bassendean	45-50	Present
WP2	3	6	Bassendean	40-45	Absent
WP3	3	6	Bassendean	40-45	Absent
WP4	3	6	Bassendean	40-45	Present
WP5	3	6	Bassendean	40-45	Absent
WP6	3	6	Bassendean	40-45	Present
YL1	2	10	Spearwood	35-40	Absent
YL2	2	10	Spearwood	30-35	Absent
YL3	2	10	Spearwood	15-20	Absent
YN1	1	9	Spearwood	35-40	Absent
YN2	1	10	Spearwood	50-55	Absent
YN3	1	10	Spearwood	60-65	Absent
YN4	4	10	Spearwood	60-65	Absent
YN5	4	10	Spearwood	35-40	Absent
YN6	4	10	Spearwood	45-50	Absent

Appendix 4: Regression coefficients of the number of mature and Carnaby's cockatoo manipulated infructescences in relation to independent variables of plant morphological characteristics per quadrat (400m^2). Significance level $P < 0.05$.

	Variables	Coeff.	SE	*F*	d.f.	*P*	r^2
B. attenuata	Constant	6.05	10.29	4.69	6,68	0.00	0.29
	Height	-1.57	0.59				
	Foliage height	0.46	0.54				
	Girth	12.39	5.41				
	Canopy area	0.17	0.15				
	No. of reproductive stems	-1.02	1.93				
	Age	0.11	0.08				
	Constant	8.70	10.19	5.17	5,69	0.00	0.27
	Height	-1.26	0.55				
	Foliage height	0.34	0.54				
	Girth	13.02	5.43				
	Canopy area	0.14	0.15				
	RPS	0.04	1.78				
	Constant	8.73	10.04	6.55	4,70	0.00	0.27
	Height	-1.25	0.43				
	Foliage height	0.34	0.54				
	Girth	13.07	5.01				
	Canopy area	0.13	0.11				
	Constant	10.30	9.67	8.68	3,71	0.00	0.27
	Height	-1.07	0.32				
	Girth	13.01	4.99				
	Canopy area	0.13	0.11				
B. menziesii	Constant	6.95	4.82	5.58	6,42	0.00	0.44
	Height	-1.09	0.34				
	Foliage height	1.37	0.48				
	Girth	9.68	5.39				
	Canopy area	0.18	0.15				
	No. of reproductive stems	-4.25	1.97				
	Age	0.10	0.73				
	Constant	6.23	4.84	6.18	5,43	0	0.42
	Height	-0.96	0.33				
	Foliage height	1.22	.47				
	Girth	10.60	5.40				
	Canopy area	0.16	0.15				
	No. of reproductive stems	-2.38	1.45				
	Constant	5.98	4.93	6.8	4,44	0	0.38
	Height	-1.16	0.31				
	Foliage height	1.04	0.46				
	Girth	6.02	4.72				
	Canopy area	0.30	0.13				
	(Constant)	8.25	5.09	5.31	4,44	0.001	0.33
	Girth	14.44	5.54				
	CanArea	0.10	0.16				
	Height	-0.84	0.35				
	RPS	-1.48	1.50				
B. sessilis	Constant	158.28	4 547.60	26.76	4,9	0.00	0.92
	Foliage height	15.62	40.17				
	Girth	608.28	474.77				
	Canopy area	390.76	153.71				
	Age	-10.67	7.47				
	Constant	1 943.11	3 634.86	109.58	1,12	0.00	0.90
	Canopy area	280.86	26.83				
	Constant	7 922.13	4 191.36	66.03	1,12	0.00	0.85
	Foliage height	86.60	10.66				
	Constant	9 176.93	5 489.32	33.29	1,12	0.00	0.74
	Height	51.20	8.88				
	Constant	10 618.46	6 047.13	24.44	1,12	0.00	0.67
	No. of reproductive stems	48.54	9.82				

Appendix 5: Habitat quality assessment equations for selected models (refer to Figure 7.6 for application in decision making).

Species	Equation
B. attenuata	y = 10.30 – (1.07 x height) + (13.01 x girth) + (0.13 x canopy area)
B. menziesii	y = 6.23 – (0.96 x height) + (1.22 x foliage height) + (10.60 x girth) + (0.16 x canopy area) – (2.38 x number of reproductive stems)
B. sessilis	y = 7 922.13 + (86.60 x foliage height)

Appendix 6: Habitat assessment example form.

Habitat assessment protocol for Carnaby's cockatoo on the Swan coastal plain

Site requirements:

- Swan coastal plain
- Remnant vegetation
- Representative banksia woodland (species composition, density etc.)
- Quadrat size: 20 m x 20 m (400 m^2)

Food Resource species

Banksia species and other dominant food resource plants present (add):

Species	Number of stems per quadrat
B. attenuata	
B. menziesii	
B. prionotes	
B. sessilis	

Carnaby's Feeding

Carnaby's cockatoo feeding evidence (circle): present / absent

Species	Structure (circle)	Intensity (circle)
B. attenuata	cone, flower, twig	high / moderate / low
B. menziesii	cone, flower, twig	high / moderate / low
B. prionotes	cone, flower, twig	high / moderate / low
B. sessilis	cone, flower, twig	high / moderate / low
	cone, flower, twig	high / moderate / low
	cone, flower, twig	high / moderate / low
	cone, flower, twig	high / moderate / low

Disease
Dieback disease (circle): present / absent
Identification (circle): soil sampling / dieback mapping / dieback interpretation
Details: If soil sampled name of company/agency who conducted testing: _____ Dieback mapping, type (e.g. aerial), date produced and custodian: _____ If disease interpretation in the field level of experience in dieback interpretation (some / moderate / considerable) and signs/symptoms: _____ _____
IF DIEBACK DISEASE IS PRESENT SELECT ANOTHER SITE
Fire history
Time since last fire (years):
Fire evidence: Fire scars / presence of fire colonist species (e.g. *Acacia pulchella*) / vegetation resprouting from base or epicormic shoots
Notes: _____ _____
IF TIME SINCE LAST FIRE IS <5 YEARS SELECT ANOTHER SITE.
Models
B. attenuata

Refer to Chapter 7
B. menziesii Refer to Chapter 7
B. prionotes Refer to Chapter 7
B. sessilis Refer to Chapter 7
Comments / notes: _____ _____ _____ _____ _____